Geological Society of America Bulletin

Cretaceous-Tertiary shortening, basin development, and volcanism in central Tibet

Paul Kapp, An Yin, T. Mark Harrison and Lin Ding

Geological Society of America Bulletin 2005;117, no. 7-8;865-878
doi: 10.1130/B25595.1

Cretaceous-Tertiary shortening, basin development, and volcanism in central Tibet

Paul Kapp†
Department of Geosciences, University of Arizona, Tucson, Arizona 85721-0077, USA

An Yin‡
T. Mark Harrison§
Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California 90095-1567, USA

Lin Ding#
Institute of Tibetan Plateau Research and Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

ABSTRACT

The geologic map pattern of the Qiangtang terrane in central Tibet defines a >600-km-long and up to 270-km-wide east-plunging structural culmination. It is characterized by early Mesozoic blueschist-bearing mélange and upper Paleozoic strata in the core and mainly Triassic–Jurassic strata along the limbs. In the western Qiangtang terrane (~84°E), the culmination is unconformably overlain by weakly deformed mid-Cretaceous volcanic flows and tuffs. Along the Bangong suture to the south (32°N, 84°E), mid-Cretaceous nonmarine red beds and volcanic rocks lie unconformably on Jurassic suture zone rocks. These relationships demonstrate that west-central Tibet was above sea level during the mid-Cretaceous and experienced significant denudation prior to mid-Cretaceous time. Growth of the Qiangtang culmination is inferred to have initiated during southward emplacement of a thrust sheet of early Mesozoic mélange and upper Paleozoic strata during the Early Cretaceous Lhasa-Qiangtang collision. The north-south width of the inferred thrust sheet provides a minimum slip estimate of ~150 km at 84°E, decreasing eastward to ~70 km at 87°E. Paleogene deformation in the Qiangtang terrane is characterized by widely distributed, mainly north-dipping thrust faults that cut Eocene–Oligocene red beds and volcanic rocks in their footwall. Along the Bangong suture, the north-dipping Shiquanhe-Gaize-Amdo thrust system cuts 64 and 43 m.y. old volcanic tuffs in its footwall and accommodated >40 km of post–mid-Cretaceous shortening. The Tertiary south-dipping Gaize–Siling Co backthrust bounds the southern margin of the Bangong suture and marks the northernmost limit of mid-Cretaceous marine strata in central Tibet. Cretaceous deformation and denudation in central Tibet is attributed to northward underthrusting of the Lhasa terrane beneath the Qiangtang terrane along the Bangong suture. This model implies that (1) Cretaceous strata along the Bangong suture and in the northern Lhasa terrane were deposited in a flexural foreland basin system and derived at least in part from the Qiangtang terrane, and (2) the central Tibetan crust was thickened substantially prior to the Indo-Asian collision. Although its magnitude is poorly known, Tertiary shortening in the Qiangtang terrane is more prevalent than in the Lhasa terrane; this difference may be attributed to the presence of underthrust mélange in the deeper central Tibetan crust, which would have made it weaker than the Lhasa terrane during the Indo-Asian collision.

Keywords: Tibet, plateau formation, continental collision, underthrusting, suture, shortening.

INTRODUCTION

There is growing geologic and geophysical evidence for growth of the Tibetan plateau by northward underthrusting of India beneath southern Tibet (e.g., Nelson et al., 1996; Owens and Zandt, 1997; DeCelles et al., 2002), lower crustal flow (e.g., Royden et al., 1997; Clark and Royden, 2000; Hodges et al., 2001; Ross et al., 2004), and major crustal shortening, basin infilling, and subduction of continental lithosphere in northern Tibet (e.g., Yin and Harrison, 2000; Tapponnier et al., 2001; Kind et al., 2002). The relative importance of these plateau-forming processes in producing the vast, internally drained part of the plateau interior remains poorly known. Also uncertain is the time interval over which the Tibetan plateau formed. A common assumption in most models is that the thick crust (>65 km) and high elevation (~5 km) of Tibet are dominantly Cenozoic features related to collision between India and Asia. The assumption that Tibet was near sea level prior to the Indo-Asian collision is based largely on the presence of marine strata as young as Eocene in age along the Indus-Yarlung suture (Fig. 1) (e.g., Burg and Chen, 1984; Searle et al., 1987, 1988) and reports of Cretaceous to Paleocene marine limestones in the Lhasa terrane (summarized in Zhang, 2000). While shallow marine limestones of Aptian–Albian age are well documented in the Lhasa terrane, the reports of younger marine strata have not been confirmed. In fact, post–mid-Cretaceous strata documented in the Lhasa terrane by other workers are entirely nonmarine (Leeder et al., 1988; Yin et al., 1988; Murphy et al., 1997; Leier et al., 2002). Further-

†E-mail: pkapp@geo.arizona.edu.
‡E-mail: yin@ess.ucla.edu.
§Present address: Institute of Advanced Studies, Australian National University, Canberra Australian Capital Territory, 0200, Australia; e-mail: mark.harrison@anu.edu.au.
#E-mail: dinglin@mail.igcas.ac.cn.

GSA Bulletin; July/August 2005; v. 117; no. 7/8; p. 865–878; doi: 10.1130/B25595.1; 8 figures; Data Repository item 2005099.

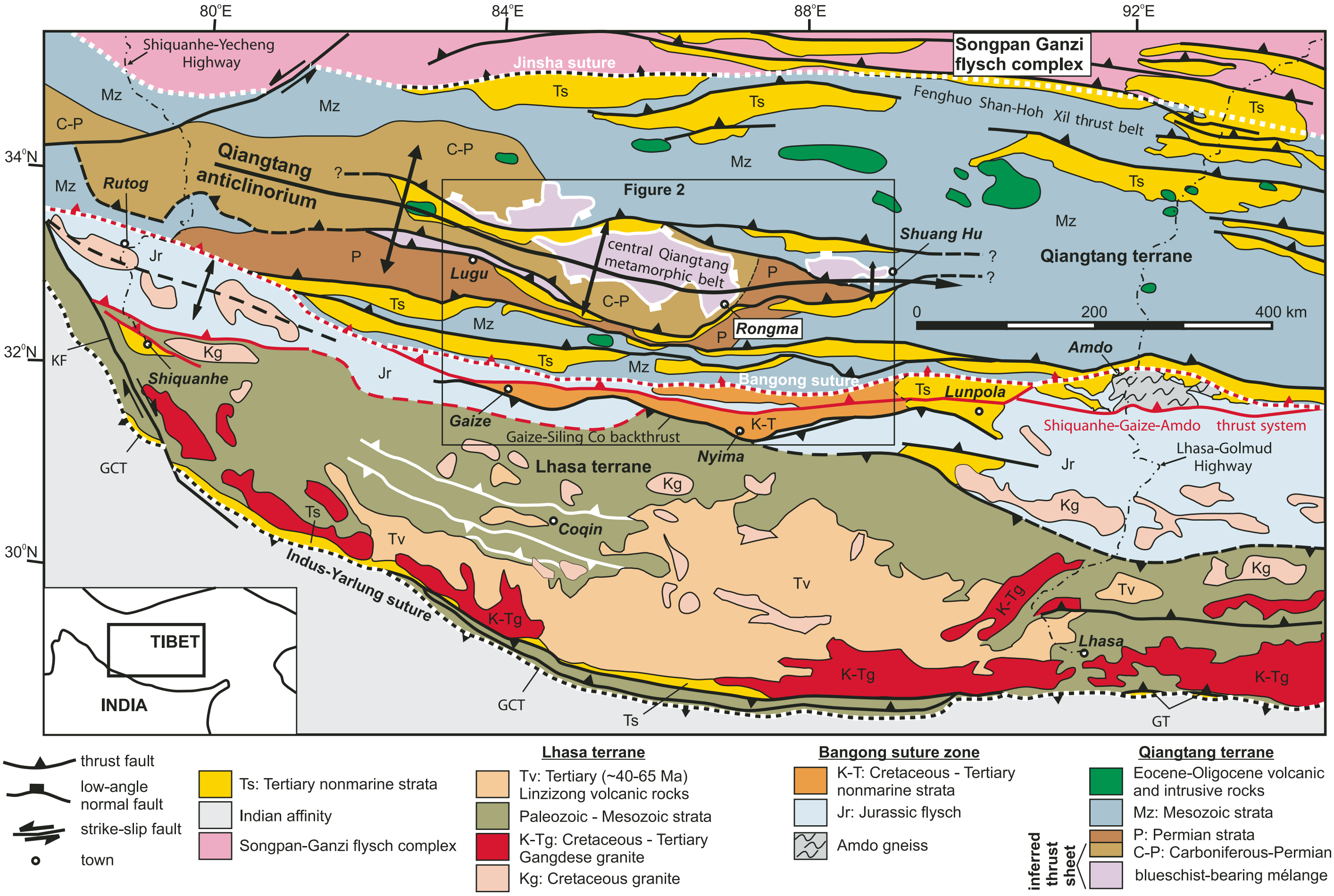


Figure 1. Tectonic map of southern and central Tibet modified from Kapp et al. (2003a). Tertiary thrust faults are shown in black. Major Mesozoic faults are shown in white: the Coqin thrust belt of Murphy et al. (1997) and early Mesozoic domal low-angle normal faults in the central Qiangtang terrane (Kapp et al., 2000, 2003b). Abbreviations: GCT—Great Counter thrust; GT—Gangdese thrust system; KF—Karakoram fault.

more, post-Jurassic marine strata have not been documented in large parts of the plateau north of the Lhasa terrane (Liu, 1988; Zhang, 2000). Thus, it is possible that large parts of Tibet were substantially elevated prior to Indo-Asian collision during Cretaceous–earliest Tertiary development of an Andean-style arc in southern Tibet (Fig. 1, Gangdese arc) and Lhasa–Qiangtang continental collision (Burg et al., 1983; England and Searle, 1986; Pan, 1993; Fielding, 1996; Murphy et al., 1997; Yin and Harrison, 2000; Ding and Lai, 2003; Kapp et al., 2003a). Numerical models of Cenozoic orogeny in Asia that incorporate precollisional topography in Tibet make very different predictions regarding the style, timing, and distribution of continental deformation from those that do not (e.g., England and Searle, 1986; Kong et al., 1997). Therefore, the uncertainty in the crustal thickening history of the plateau interior limits not only our understanding of the mechanisms and time scales of continental plateau formation, but also our ability to quantify continental deformation during the Indo-Asian collision.

This paper presents the first comprehensive overview of the Cretaceous–early Tertiary geology of a large (>85,000 km^2) region in the middle of the Tibetan plateau (outlined area in Fig. 1). It is based on ~175 days of geologic mapping at 1:100,000 scale and geochronologic studies (details of methods available as supplementary information, see DR1[1]) along the Bangong suture and two traverses across the Qiangtang terrane (Fig. 2A).[2] Our new data bearing on the Cretaceous-Tertiary history of crustal shortening, denudation, basin development, and magmatism in central Tibet are integrated with those existing for the Lhasa terrane into a new tectonic model for crustal thickening and plateau growth.

[1]GSA Data Repository item 2005099, geochronologic methods and Tables DR1 and DR2, is available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

[2]Figure 2 is on an insert accompanying this issue.

REGIONAL GEOLOGIC BACKGROUND

The Qiangtang terrane (Fig. 1) exposes mainly Carboniferous and younger strata and early Mesozoic blueschist-bearing mélange of the central Qiangtang metamorphic belt (Cheng and Xu, 1986; Liu, 1988; Kapp et al., 2000; Kapp et al., 2003b). Cretaceous strata are scarcely exposed, and the history of pre-Indo-Asian collision shortening is poorly known (Cheng and Xu, 1986; Kidd et al., 1988; Leeder et al., 1988; Yin et al., 1988). Paleogene strata are nonmarine and crop out within relatively narrow (<20-km-wide) east-trending basins that locally contain 50–29 Ma potassic volcanic rocks (Cheng and Xu, 1986; Deng, 1989; Chung

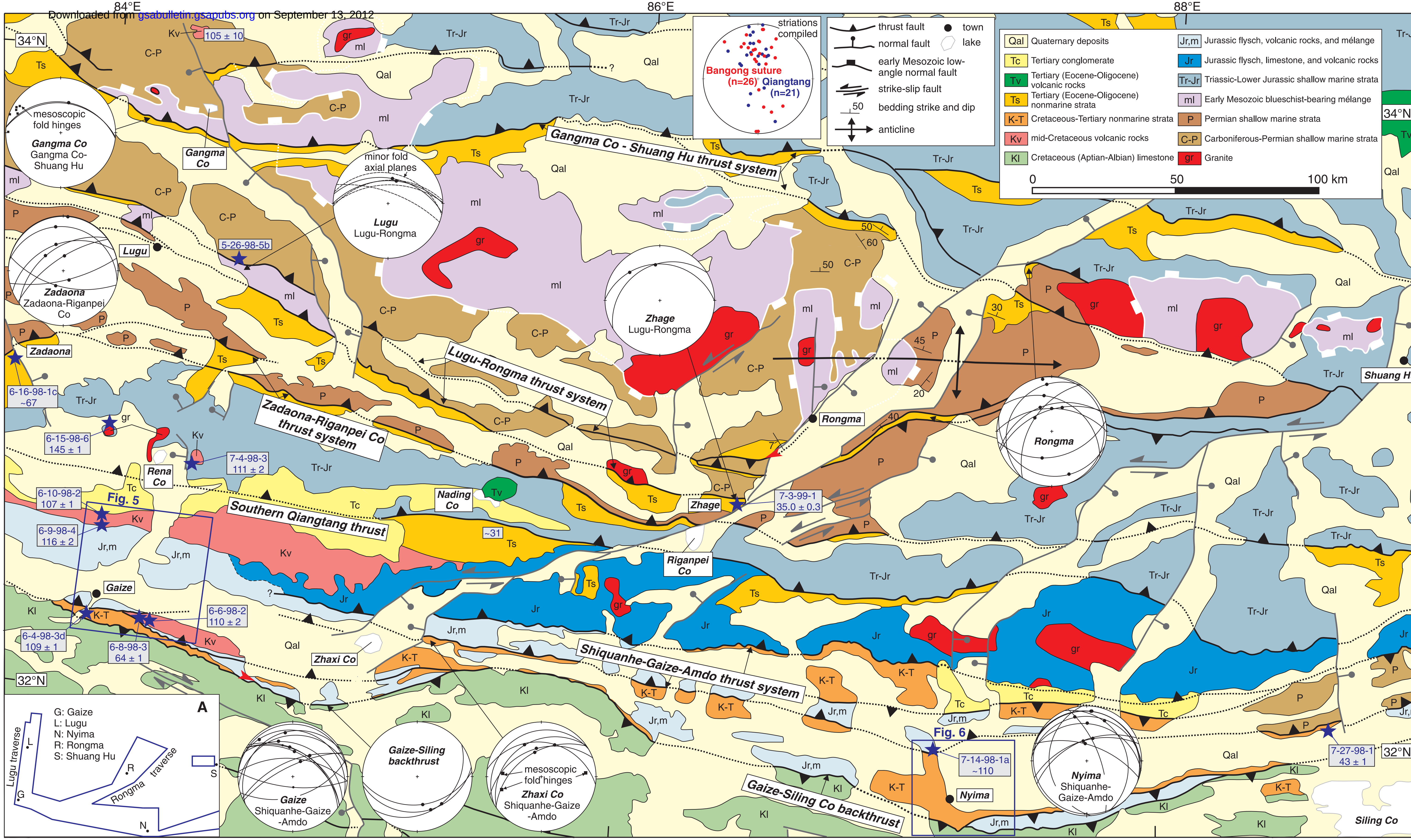


Figure 2. Geologic map of central Tibet. (A) Inset shows areas that have been mapped at 1:100,000 scale (Kapp et al., 2003b; this study). The geology between map areas is based on our interpretations of satellite imagery and 1:1,000,000-scale (Cheng and Xu, 19886) and 1:1,500,000-scale (Liu, 1988) geologic maps. Structural measurements are plotted on lower hemisphere equal-area stereonets. Blue stars show geochronologic sample localities with sample numbers and interpreted crystallization ages (in Ma and analytical uncertainties at 2σ). Stratigraphic age assignments, if not constrained from our studies, were based on correlating observed lithostratigraphy with nearby biostratigraphic sections (Cheng and Xu, 19886; Li and Zheng, 1993; Li et al., 1995) and should be considered tentative.

Cretaceous-Tertiary shortening, basin development, and volcanism in central Tibet
Paul Kapp, An Yin, T. Mark Harrison, and Lin Ding
Figures 2 and 5

Supplement to: *Geological Society of America Bulletin*, v. 117, no. 7/8

et al., 1998; Deng et al., 2000; Wang et al., 2001; Horton et al., 2002; Ding et al., 2003; Spurlin et al., 2005). Some exposures of Eocene-Oligocene granitoids have also been documented in the northern Qiangtang terrane (Hacker et al., 2000; Roger et al., 2000). Minimal Tertiary upper-crustal shortening characterizes the interior of the Qiangtang terrane along the Lhasa-Golmud Highway (Coward et al., 1988), central Qiangtang metamorphic belt (Kapp et al., 2003b), and Yecheng-Shiquanhe Highway in far western Tibet (Fig. 1) (Matte et al., 1996). By contrast, along and to the east of the Lhasa-Golmud Highway, the northern Qiangtang terrane was shortened a minimum of 40%–50% by the Tertiary Fenghuo Shan-Hoh Xil (Fig. 1) and Yushu–Nanqian thrust systems (Coward et al., 1988; Kidd et al., 1988; Yin and Harrison, 2000; Liu and Wang, 2001; Liu et al., 2001; Horton et al., 2002; Spurlin et al., 2005).

The Bangong suture zone is characterized by a >1200-km-long east-trending belt of mainly Jurassic flysch, mélange, marine conglomerate, and volcanic rocks, which are associated with scarce but widely scattered ophiolitic fragments (Wang et al., 1983; Cheng and Xu, 1986; Liu, 1988; Yin et al., 1988; Schneider et al., 2003). It represents remnants of an oceanic basin between the Qiangtang and Lhasa terranes that closed by northward subduction beneath the Qiangtang terrane and possibly one or more oceanic island arc terranes during Middle Jurassic to Early Cretaceous time (Girardeau et al., 1984; Tang and Wang, 1984; Pearce and Deng, 1988). The trace of the suture is defined to lie along the northernmost exposures of suture zone rocks (Fig. 1). The Bangong suture zone was modified by thrusting subsequent to ocean closure (Cheng and Xu, 1986; Cheng and Xu, 1987; Coward et al., 1988; Kidd et al., 1988; Ratschbacher et al., 1994; Matte et al., 1996; Yin and Harrison, 2000; Kapp et al., 2003a; Wu et al., 2004). Hindering estimates for the timing and magnitude of shortening are the scarcity of structural studies and age information on nonmarine strata that could be either Cretaceous or Tertiary (see discussion by Kidd et al., 1988). Recent studies of the Bangong suture zone in westernmost Tibet provide a preliminary minimum estimate of >97 km for Late Cretaceous–early Tertiary shortening, however, and raise the possibility for significant reactivation before and during the Indo-Asian collision (Kapp et al., 2003a).

Cretaceous sedimentary sequences comprise ~50% of the exposed bed rock in the Lhasa terrane (Liu, 1988). They are >3 km thick and consist of pre-Albian fluvial (north Lhasa terrane) and marginal marine (south Lhasa terrane) deposits, an overlying shallow marine limestone-bearing unit of Aptian-Albian age (between ca. 121 and 99 Ma), and an upper unit of fluvial red beds (includes the Takena Formation) (Leeder et al., 1988; Yin et al., 1988; Leier et al., 2002; Zhang et al., 2004). It is debated whether Cretaceous strata were deposited in an extensional back-arc (Zhang, 2000; Zhang et al., 2004), intra-arc (Pan, 1993), retro-arc foreland (England and Searle, 1986), or peripheral foreland basin related to Lhasa-Qiangtang continental collision (Leeder et al., 1988; Yin et al., 1994; Kapp et al., 2003a).

Latest Cretaceous–early Tertiary rocks in the Lhasa terrane are dominated by volcanic sequences of the Linzizong Formation (Fig. 1), which have been dated at 68–49 Ma near Lhasa (Maluski et al., 1982; Xu et al., 1985; Coulon et al., 1986; Pan, 1993; He et al., 2003) and 54–37 Ma in southwestern Tibet (Miller et al., 2000). Exposures of Tertiary sedimentary basin fill are scarce within the interior of the Lhasa terrane (Liu, 1988). Intrusive igneous rocks are widespread in the Lhasa terrane (Fig. 1) and have been divided into two belts: a northern belt that includes Early Cretaceous peraluminous granites (Xu et al., 1985; Harris et al., 1990) and the mainly dioritic Late Cretaceous–Tertiary Gangdese belt in the southern Lhasa terrane (e.g., Debon et al., 1986). The petrogenesis of the northern Lhasa terrane belt has been attributed to (1) crustal anatexis during Lhasa-Qiangtang continental collision (Xu et al., 1985; Pearce and Mei, 1988), (2) high-temperature crustal anatexis related to mantle attenuation and associated asthenospheric upwelling following Lhasa-Qiangtang continental collision (Harris et al., 1990), or (3) low-angle northward subduction of Neo-Tethys oceanic lithosphere (Coulon et al., 1986; Ding et al., 2003; Zhang et al., 2004). Gangdese plutonism and Linzizong volcanism are widely attributed to northward subduction of the Neo-Tethys Ocean along the Indus-Yarlung suture (Fig. 1) prior to the Indo-Asian collision (e.g., Dewey and Bird, 1970; Tapponnier et al., 1981; Allègre et al., 1984; Debon et al., 1986). Still unexplained, however, is why magmatism of similar geochemistry to precollisional batholith rocks (high-K calc-alkaline) continued in the Gangdese belt until Late Miocene time (D'Andrea et al., 1999; Miller et al., 1999; Harrison et al., 2000).

Throughout much of the Lhasa terrane, gently folded Linzizong volcanic rocks rest unconformably on strongly deformed Cretaceous and older rocks (Tapponnier et al., 1981; Burg et al., 1983; Allègre et al., 1984; Pan, 1993; Murphy et al., 1997; Ding and Lai, 2003). This relationship demonstrates that major upper crustal shortening predates the Indo-Asian collision in large areas of the Lhasa terrane. In the Coqin area (Fig. 1), Murphy et al. (1997) documented >180 km of Cretaceous upper crustal shortening. In the Lhasa area (Fig. 1), the Upper Cretaceous Takena Formation was shortened by ~40% prior to Linzizong volcanism (Pan, 1993).

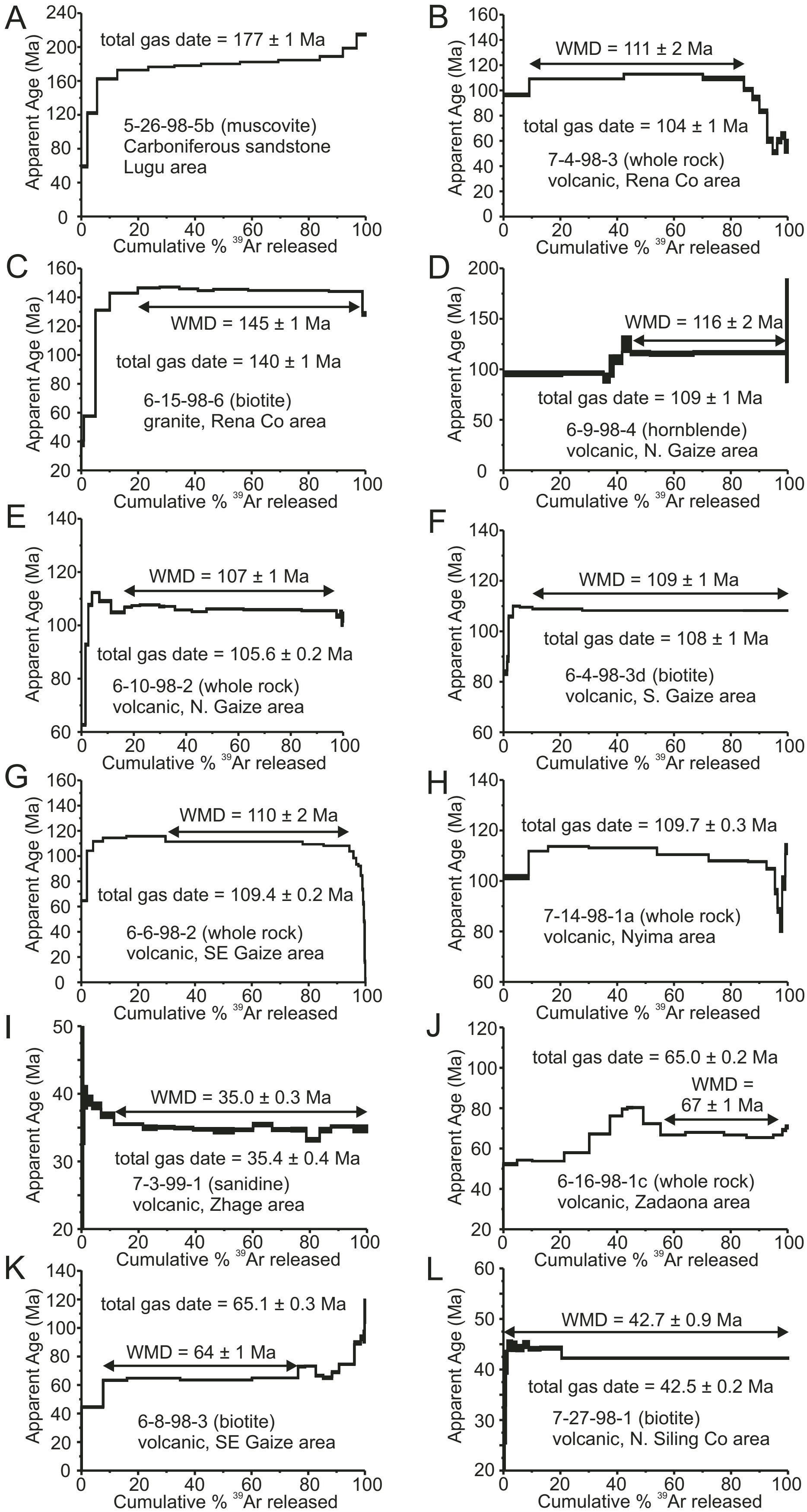
CRETACEOUS SHORTENING, BASIN DEVELOPMENT, AND VOLCANISM

Qiangtang Terrane

Between 80°E and 89°E, the regional geologic map pattern of the Qiangtang terrane can be described as a >600-km-long and up to 270-km-wide east-plunging structural culmination with upper Paleozoic strata and metamorphic rocks in its core, and Mesozoic strata along its limbs (Fig. 1) (Qiangtang anticlinorium of Yin and Harrison, 2000). The metamorphic rocks consist of early Mesozoic blueschist-bearing tectonic mélange and were exhumed to upper crustal levels in the footwall of Late Triassic–Early Jurassic crustal-scale normal faults (Figs. 1 and 2; Kapp et al., 2000, 2003b). This normal faulting structurally elevated the metamorphic rocks with respect to hanging-wall upper Paleozoic–early Mesozoic strata but cannot explain the present structural elevation of upper Paleozoic strata. Additionally, metamorphic rocks in the western part of the belt were likely at deeper structural levels than those in the east following early Mesozoic normal faulting because hanging-wall strata become progressively younger from west to east (Figs. 1 and 2) (Carboniferous near Gangma Co, Carboniferous–Permian near Rongma, and Upper Triassic–Lower Jurassic near Shuang Hu; Kapp et al., 2003b). This inference is supported by a $^{40}Ar/^{39}Ar$ step-heating experiment on muscovite from a sample of Upper Carboniferous micaceous sandstone ~25 km east of Lugu (5-26-98-5b; Fig. 2). The sample yields a monotonically rising $^{40}Ar/^{39}Ar$ age spectrum with apparent ages ranging between 59 Ma and 215 Ma (Fig. 3A; Table DR1 [see footnote 1]), characteristic of slow cooling within the argon partial retention zone (McDougall and Harrison, 1999). The total gas date of ca. 177 Ma provides an estimate of when the sandstone cooled to below the bulk closure temperature of muscovite (300–350 °C; McDougall and Harrison, 1999). It suggests that this region of the west-central Qiangtang terrane was significantly buried until at least Middle Jurassic time. Subsequent exhumation likely occurred during growth of the regional east-plunging culmination.

Mapping and geochronologic studies along the Lugu traverse (Fig. 2A) demonstrate that major growth of the Qiangtang culmination occurred by mid-Cretaceous time. Approximately 30 km north of Gangma Co (Fig. 2)

Figure 3. $^{40}Ar/^{39}Ar$ apparent age spectra. Uncertainties for total gas dates and weighted mean dates (WMD) are at the 1σ and 2σ level, respectively, and do not include uncertainties in the J factor or decay constants. Details of the $^{40}Ar/^{39}Ar$ method and tabulated results are available in the data repository, DR1 [see footnote 1].



(Co = lake in Tibetan), Carboniferous quartzites and strongly cleaved slates are unconformably overlain by a >200-m-thick sequence of gently dipping subaerial volcanic flows and tuffs, which yielded total fusion $^{40}Ar/^{39}Ar$ dates on single sanidine crystals between ca. 95 Ma and ca. 132 Ma (Fig. 3; Yin et al., 1999b). Nearly flat-lying volcanic tuffs are also preserved ~130 km to the south near Rena Co (Fig. 2), where they lie unconformably on strongly folded Triassic-Jurassic turbiditic sandstone and limestone. A whole-rock sample of volcanic tuff (7-4-98-3) yields three steps between 10 and 80 cumulative % ^{39}Ar released with a weighted mean $^{40}Ar/^{39}Ar$ date of 111 ± 2 Ma, which we interpret to be the age of volcanism (Fig. 3B; Table DR1 [see footnote 1]). The preservation of nearly flat-lying mid-Cretaceous subaerial volcanic rocks overlying older, strongly deformed rocks in the Qiangtang terrane demonstrates that this area of central Tibet experienced significant upper crustal deformation and denudation prior to, was above sea-level during, and experienced limited denudation since, mid-Cretaceous time.

Triassic-Jurassic strata of the southern Qiangtang terrane are intruded by a discontinuous east-west belt of mainly biotite-bearing granites (Fig. 2). In the west near Rena Co (Fig. 2), the granites are associated with andalusite-bearing contact metamorphic aureoles. A granite sample west of Rena Co (6-15-98-6; Fig. 2) yields concordant to slightly discordant U-Pb ion microprobe spot dates on seven single zircons between ca. 145 Ma and ca. 160 Ma (Fig. 4, Table DR2 [see footnote 1]). Biotite from the same sample yields a weighted mean $^{40}Ar/^{39}Ar$ plateau date of 145 ± 1 Ma over ~80% cumulative ^{39}Ar released (Fig. 3C). This age estimate lies within uncertainty of the youngest zircon date and is interpreted to be the crystallization age of the granite; older zircon dates are attributed to variable amounts of radiogenic Pb inheritance. These results suggest that the granite was emplaced and rapidly cooled at a relatively shallow crustal level, placing limits on the magnitude of post-Jurassic denudation in the southern Qiangtang terrane. Furthermore, they are the first to document the presence of Late Jurassic plutonism north of the Bangong suture.

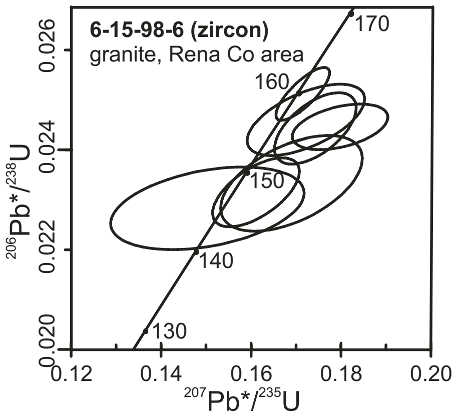


Figure 4. U-Pb concordia plot showing results of single spot ion-microprobe analyses on zircon from a granite near Rena Co (Fig. 2). Error ellipses are shown at the 2σ level. Details of the U-Pb method and tabulated results are available in the data repository.

Bangong Suture

In the study area, the Bangong suture is defined by an ~30-km-wide east-trending belt of strongly cleaved and transposed rocks of primarily Jurassic age (Fig. 2). They consist of turbiditic graywacke, chert, sandy limestone, volcanic rocks, and sedimentary-, metamafic-, and serpentinite-matrix tectonic mélanges. Metabasites exhibit greenschist-facies mineral assemblages; no blueschists were observed.

Jurassic rocks of the Bangong suture are unconformably overlain by sequences of fluvial pebble conglomerate, sandstone, and siltstone, volcanic rocks, and multi-colored lacustrine mudstone and marl (Figs. 2, 5, and 6).[3] These rocks have been interpreted previously as Triassic, Cretaceous, or Tertiary in age (Cheng and Xu, 1986; Liu, 1988). North of Gaize (~20 km), red beds overlie hornblende-bearing volcanic rocks (Kv1; Fig. 5). Slightly altered hornblende from one sample (6-9-98-4; Figs. 2 and 5) provides a stair-step-shaped ^{40}Ar/^{39}Ar spectrum with an older plateau that yields a weighted mean date of 116 ± 2 Ma over the last 45% ^{39}Ar released (Fig. 3D), which we interpret to be the age of volcanism. The younger apparent ages provided during the earlier stages of step heating are attributed to degassing of alteration products. In the same area, red beds are also overlain by volcanic sequences, consisting of andesitic to dacitic flows, tuffs, and volcanic breccias and agglomerates. A whole-rock sample of andesite directly above the red beds (6-10-98-2; Figs. 2 and 5) yields a weighted mean ^{40}Ar/^{39}Ar date of 107 ± 1 Ma over ~75% ^{39}Ar released (Fig. 3E). To the south of Gaize, red beds are overlain by up to 300 m of purple volcanic tuffs. Biotite from a porphyritic dacite (6-4-98-3d) and a whole-rock sample of aphanitic tuff (6-6-98-2) (Figs. 2 and 5) yield slightly disrupted ^{40}Ar/^{39}Ar apparent age spectra with weighted mean plateau dates of 109 ± 1 Ma and 110 ± 2 Ma, respectively (Figs. 3F and 3G). Pebbles in the underlying conglomerates include rocks that are similar to those observed for the overlying Cretaceous volcanic rocks. This suggests that nonmarine sedimentation near Gaize was likely coeval with volcanism and occurred shortly prior to the dated volcanism. North of Gaize (~16 km), a south-dipping thrust with Jurassic mélange in the hanging wall cuts the lower volcanic unit (Kv1) and overlying red beds (Ks) in the footwall but is buried by the upper volcanic unit (Kv2) (Fig. 5). This relationship demonstrates that shortening was occurring during mid-Cretaceous basin development.

Volcanic interbeds were not observed in nonmarine strata along the Bangong suture east of Gaize. However, ~15 km northwest of Nyima (Figs. 2 and 6), buff-colored volcanic tuffs crop out as a 10-m-scale tectonic sliver within a north-dipping thrust-fault zone that juxtaposes strongly cleaved Jurassic strata in the hanging wall southward against red fluvial sandstone and conglomerate. One whole-rock sample (7-14-98-1a; Figs. 2 and 6) yields a disturbed ^{40}Ar/^{39}Ar age spectrum with a total gas date of ca. 110 Ma (Fig. 3H), similar to the ages of volcanic rocks in the Gaize area. Because the red beds occur in the footwall of the thrust fault and include clasts of volcanic rocks similar to those of the tectonic sliver, we infer that they are younger than ca. 110 Ma.

Near Nyima, a >3-km-thick section of nonmarine strata is deformed into an east-west–trending syncline (Fig. 6). The section comprising the southern limb of the syncline is well exposed along the banks of a north-flowing river that runs through Nyima. Its base is not exposed because of a north-dipping thrust that cuts the nonmarine strata to the south. The lower part consists mainly of interbedded lacustrine marl, mudstone, and rippled sandstone. The section coarsens upward into fluvial-trough cross-stratified sandstone and conglomerate. Immediately west of Nyima, north dip angles decrease from ~80° to <20°, and individual beds thicken northward toward the axis of the syncline over a distance of ~2 km (Figs. 6 and 7A), indicating that folding was occurring during deposition. We do not know if these strata are Cretaceous in age, like those near Gaize to the west, or rather are correlative to fluvial and lacustrine deposits of reportedly Paleocene to Oligocene age within the Lunpola basin to the east (Fig. 1) (Yu and Zheng, 1979; Ai et al., 1998; Luo et al., 1996).

[3] Figure 5 is on an insert accompanying this issue.

TERTIARY SHORTENING, BASIN DEVELOPMENT, AND VOLCANISM

Tertiary upper crustal shortening in central Tibet is in general expressed by km-scale, upright to south-directed folds and variably spaced (from ~2 km to >40 km) thrust faults that cut footwall Tertiary nonmarine strata (Fig. 2). The thrust faults are predominantly north dipping. All major east-trending ranges we studied with relief of ~1 km are composed of hanging-wall rocks that vary in age and lithology depending on location (Fig. 2). Most of these ranges exhibit asymmetric north-south topographic profiles with steeper slopes in the south than in the north; north-dipping thrust faults are located near the base of the steeper southern range fronts. Exposures of footwall Tertiary strata in the Qiangtang terrane are generally restricted to parallel valleys, where not buried by Quaternary deposits, ubiquitously dip northward (either upright or overturned) directly beneath the thrust faults, and in most areas were observed to onlap depositionally older rocks to the south. With these relationships between topography and geology established, analysis of topographic and Chinese geologic maps (Cheng and Xu, 1986; Liu, 1988) and satellite images suggests that the major east-west–striking thrust systems are laterally continuous over distances of >400 km (Fig. 2).

We found excellent exposures of almost every thrust fault mapped along the traverses shown in Figure 2A. The thrust faults are characterized by either discrete surfaces, zones of breccia and gouge that range from centimeters to tens of meters in thickness, or meter-scale thrust fault slivers that may be of either hanging wall or footwall affinity. Locally, thrust fault dips range from subhorizontal to ~45°, with steeper dips (~40°) being most prevalent. In no places were subhorizontal thrust faults, which in a few places underlie klippen, observed to extend more than ~2 km from the regional thrust fault traces. Kilometer- to mesoscopic-scale folds in hanging-wall and footwall strata are dominantly east-west–trending and slickenlines on major thrust faults, and minor synthetic and antithetic thrust fault surfaces plunge toward the north or south, indicating a north-south direction of transport (Fig. 2, see stereonets). Chatter marks, small-scale drag folds, vein-filled en echelon tension gashes, and cleavage orientations within thrust fault zones (widely noted but not measured) and overturned synclines in footwall strata consistently indicate upward transport of the hanging wall relative to the footwall.

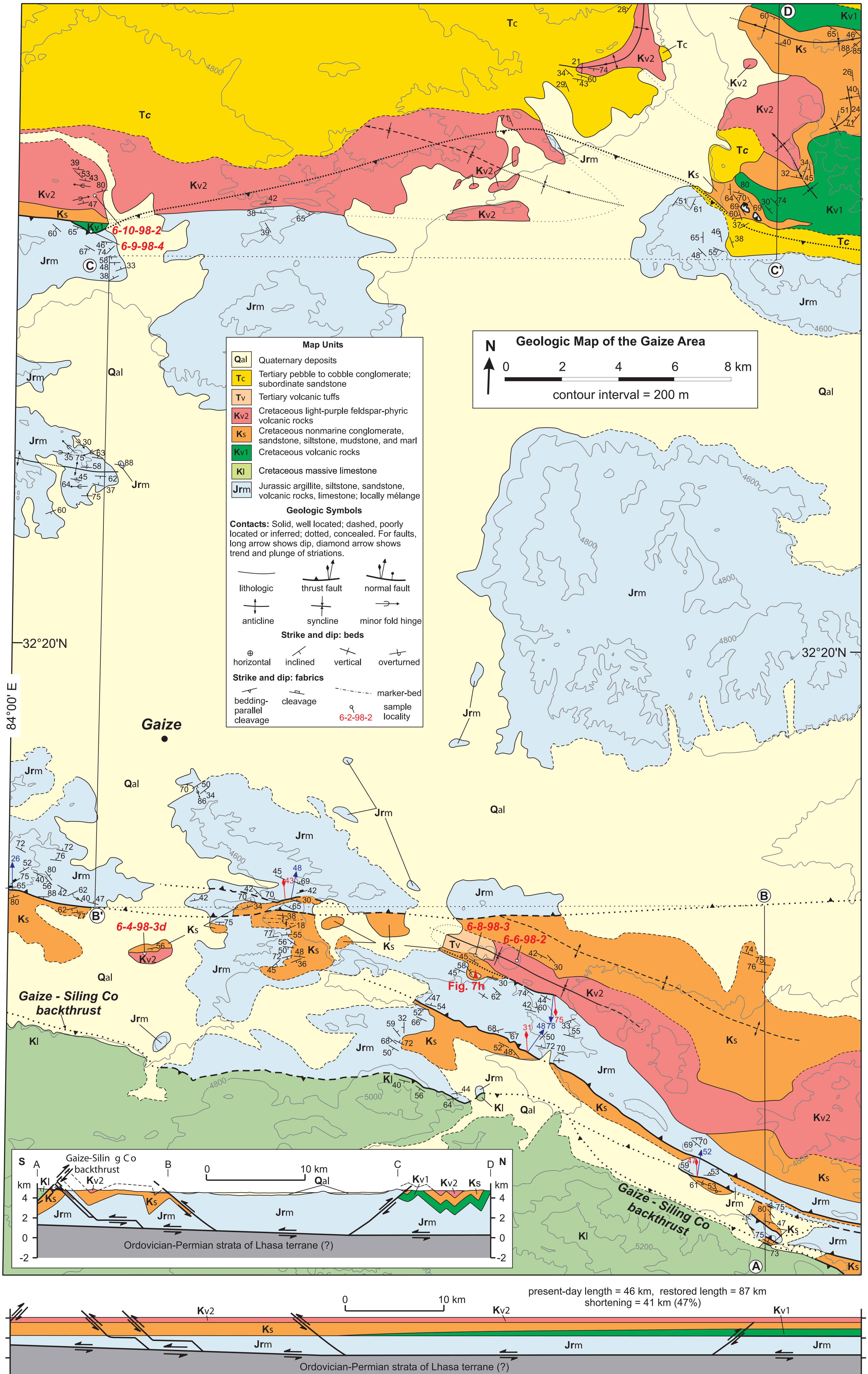


Figure 5. Geologic map and cross section of the Gaize area.

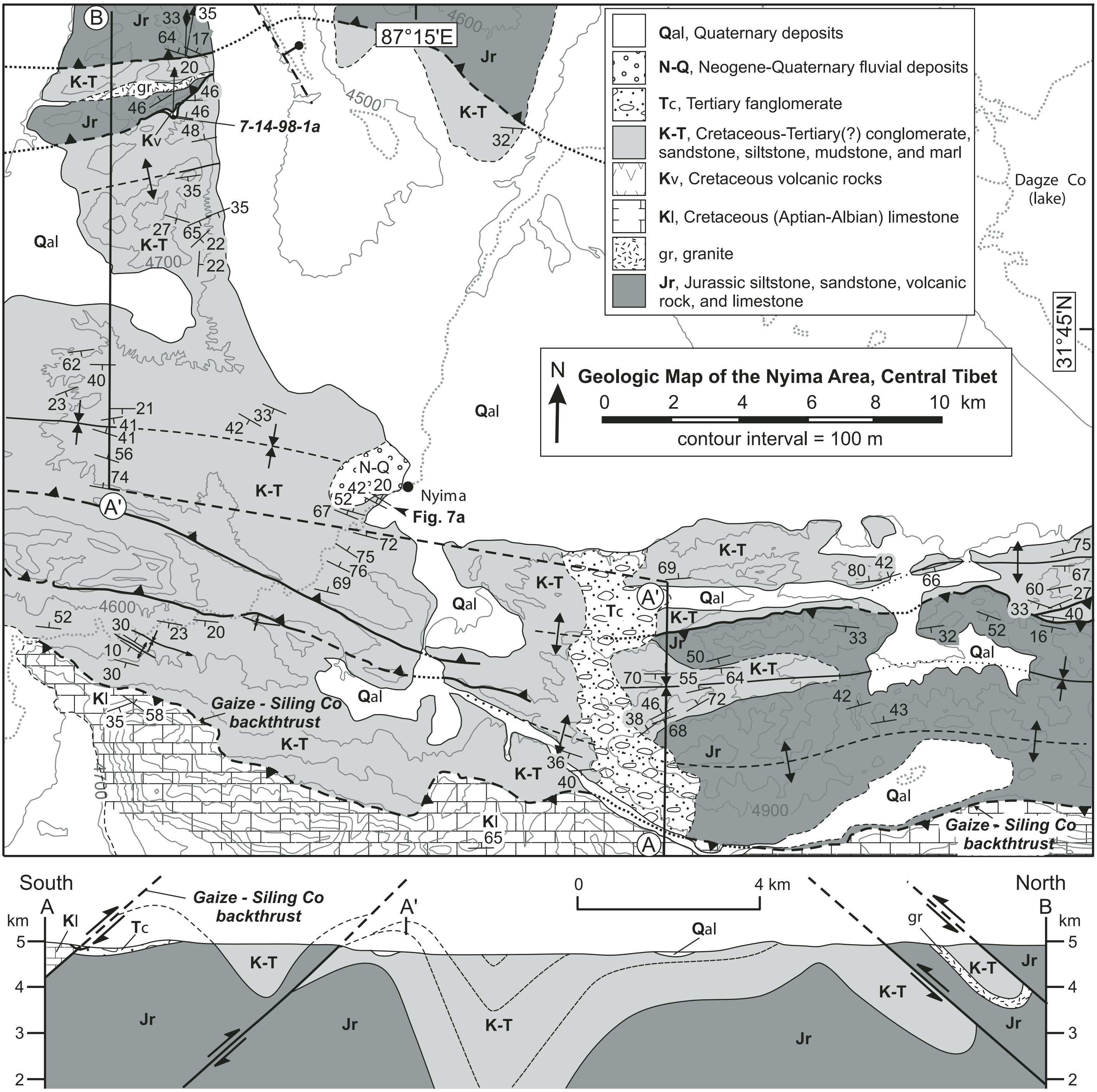


Figure 6. Geologic map and cross section of the Nyima area.

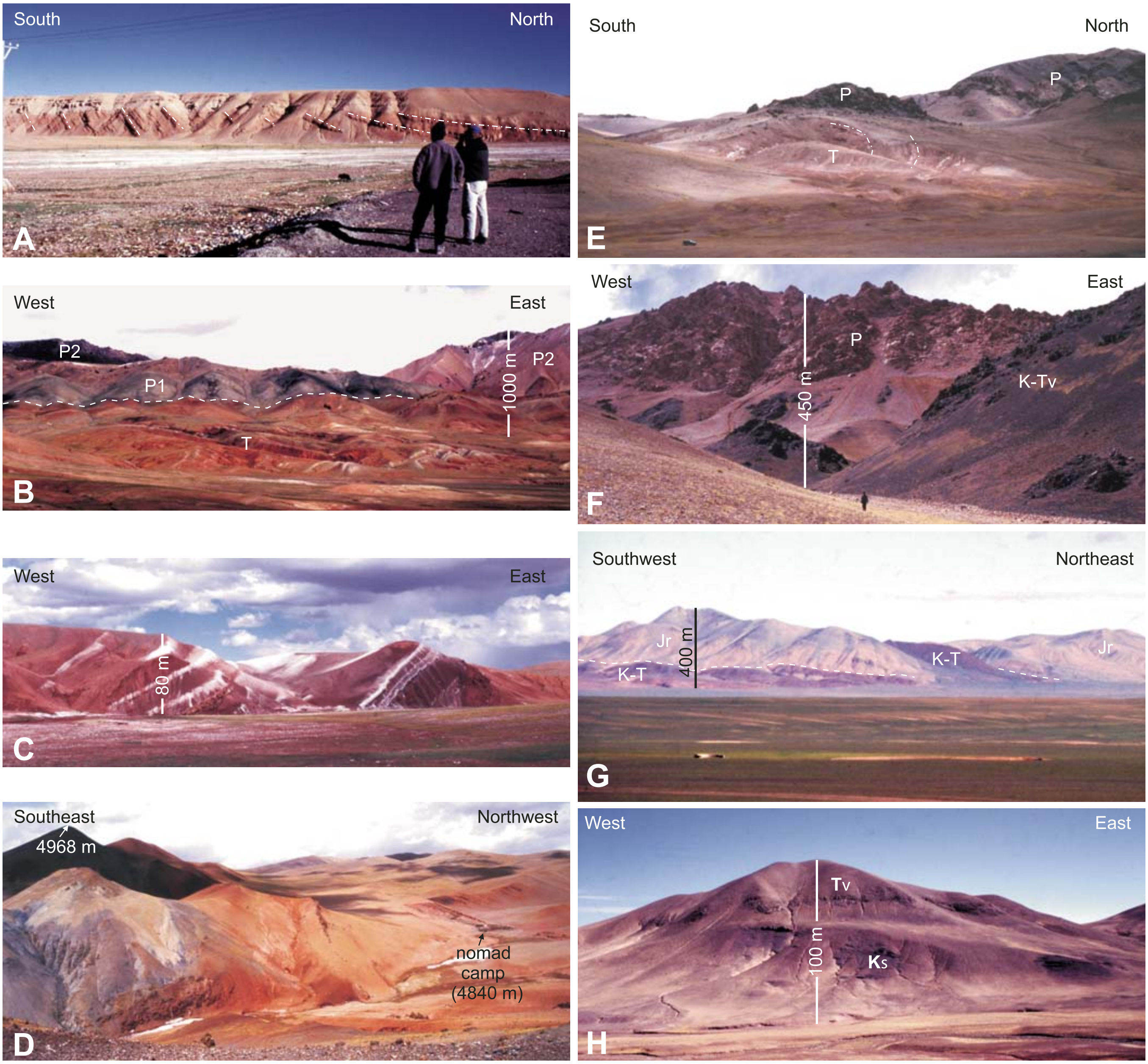


Figure 7. (A) Synorogenic nonmarine strata near Nyima (Fig. 5) as indicated by the northward fanning of dips toward shallower angles along the south limb of a syncline. The red beds are overlain by Neogene-Quaternary(?) fluvial conglomerate. (B) North-dipping thrust fault near Zhage (Fig. 2), which juxtaposes Permian volcaniclastic sandstone and turbidites (P1) and conformably overlying limestone (P2) in the hanging wall against Tertiary red beds in the footwall. (C) Gypsiferous Tertiary basin fill in the footwall of the Lugu-Rongma thrust system near Zhage (Fig. 2). (D) Southeast-dipping backthrust associated with the Lugu-Rongma thrust system near Rongma (Fig. 2), which places early Mesozoic mélange over Tertiary red beds. (E) Gently north-dipping thrust fault near Zadaona (Fig. 2) juxtaposing Permian limestone (P) in the hanging wall against Tertiary red beds in the footwall, which are deformed into an overturned syncline. (F) North-dipping thrust fault near Zadaona (Fig. 2) placing Permian limestone (P) on top of overturned Cretaceous-Tertiary volcanic rocks (K-Tv). (G) Imbricate north-dipping thrust faults ~15 km northwest of Nyima (Fig. 6), which repeat Jurassic rocks (Jr) in the hanging wall and Cretaceous-Tertiary(?) red beds (K-T) in the footwall. (H) Broadly folded ca. 64 Ma volcanic tuffs (Tv) unconformably overlying more steeply dipping mid-Cretaceous red beds (Ks) near Gaize (Fig. 5).

Qiangtang Terrane

We assign thrust faults in the Qiangtang terrane to the Gangma Co–Shuang Hu and Lugu–Rongma thrust systems in the north and the Zadaona–Riganpei Co thrust system and Southern Qiangtang thrust fault in the south (Fig. 2). The Gangma Co–Shuang Hu thrust system is represented by the Gangma Gangri thrust system along the Lugu traverse, which cuts Carboniferous sandstone and limestone, blueschist-bearing mélange, and Tertiary red beds (see Kapp et al., 2003b for more detailed description). Its along-strike equivalent ~70 km to the west (not shown on Fig. 2) is the Buergahu thrust of Ding et al. (2003), which places Carboniferous strata southward over Tertiary red beds. About 5 km south of the Buergahu thrust, Tertiary strata are conformably overlain by 30 ± 1 Ma potassic lavas; both the strata and the lavas are gently folded (Ding et al., 2003), providing evidence that shortening in central Tibet persisted until at least Oligocene time. To the east along the Rongma traverse (Fig. 2), two mapped splays of the Gangma Co–Shuang Hu thrust system involve upper Paleozoic, Triassic-Jurassic, and Tertiary strata and in some places juxtapose Triassic-Jurassic strata on top of upper Paleozoic strata. A map and description of the northern splay have been published previously (Taylor et al., 2003). Footwall Tertiary strata are locally >2 km thick and characterized by basal conglomerates with clasts derived from underlying lithologies. These conglomerates fine upward into variably colored (red, yellow, and green) sandstone, siltstone, and mudstone interpreted to be near-shore lacustrine and lacustrine fan-delta deposits. The lacustrine deposits are in turn unconformably overlain by fluvial sandstone and conglomerate.

The Lugu-Rongma thrust system is represented by the Nianta-Danguo and Lugu thrust faults (Kapp et al., 2003b) along the Lugu traverse, which cut Tertiary landslide deposits and fluvial red beds in the footwall. Along the Rongma traverse, footwall Tertiary strata in the Zhage area (Fig. 2) exceed 2 km in thickness and consist of red and green mudstone, trough cross-stratified sandstone, and conglomerate with clast rock types similar to those of hanging-wall Permian strata (Fig. 7B). Gypsiferous layers and veins in the red beds (Fig. 7C) may suggest basin deposition in an arid environment. Sanidine separated from a sample of interbedded tuff (7-3-99-1; Fig. 2) yielded a weighted mean $^{40}Ar/^{39}Ar$ plateau date of 35.0 ± 0.3 Ma (Fig. 3I; Table DR1 [see footnote 1]).

Between the Gangma Co–Shuang Hu and Lugu-Rongma thrust systems along the Rongma traverse, bedding orientations in upper Paleozoic and Tertiary strata define a >75-km-wide east-plunging antiform (Fig. 2). The traces of the Gangma Co–Shuang Hu and Lugu-Rongma thrust systems also change to a more northwest-southeast and northeast-southwest orientation, respectively, around the hinge zone of the antiform. Near Rongma, the Lugu-Rongma thrust system includes the only south-dipping thrust faults mapped in the Qiangtang terrane, which form antithetic faults to the north to northwest–dipping thrusts (Fig. 7D). We infer that these antithetic faults initiated due to buckling stresses related to development of the antiform. Involvement of Tertiary strata demonstrates that the large-wavelength fold is a Cenozoic feature. However, upper Paleozoic strata and blueschist-bearing mélange near Rongma must have been exhumed to the surface prior to deposition of unconformably overlying Tertiary strata. We infer that this exhumation occurred prior to the Indo-Asian collision based on the preservation of the mid-Cretaceous unconformity along the Lugu traverse (Fig. 2).

Along much of its length, the Zadaona–Riganpei Co thrust juxtaposes Permian strata in the hanging wall against Triassic-Jurassic strata and Tertiary fluvial sandstone and conglomerate in the footwall (Fig. 2). West of the Lugu traverse near Zadaona (Fig. 2), Tertiary red beds locally overlie andesitic volcanic rocks. Footwall strata are deformed into an overturned syncline (Fig. 7E), and in some places, Permian limestone is juxtaposed directly against overturned andesitic volcanic rocks (Fig. 7F). One whole-rock sample of andesite (6-16-98-1c) yields a complicated hump-shaped $^{40}Ar/^{39}Ar$ age spectrum with apparent ages ranging from 50 to 80 Ma (Fig. 3J). The total gas date (65.0 ± 0.2 Ma; 1σ) and weighted mean date of a plateau between 55 and 98% ^{39}Ar released (67 ± 1 Ma; 2σ) are similar to dates obtained from volcanic rocks exposed to the south near Rena Co (59 ± 2 Ma; Ding et al., 2003) and Gaize (ca. 64 Ma; this study, see below) (Fig. 2) and therefore may be geologically meaningful.

The Southern Qiangtang thrust (Fig. 2) is interpreted to represent an important lithotectonic boundary. In the hanging wall are Triassic-Jurassic shallow marine limestone and sandstone and marginal marine clastic rocks that were likely deposited on older Qiangtang terrane strata. These rocks were juxtaposed southward over footwall Jurassic turbiditic graywacke, volcanic rocks, chert, and limestone that were deposited within the Bangong Ocean and interpreted to represent remnants of an intra-arc or forearc basin system that developed on transitional or oceanic basement. Between the Lugu and Rongma traverses, near Nading Co (Fig. 2), the Southern Qiangtang thrust cuts Tertiary red beds and ca. 31 Ma volcanic rocks in the footwall (no uncertainty provided; Cheng and Xu, 1986).

Within the central Qiangtang terrane, early Mesozoic low-angle normal (detachment) faults occur in both the hanging wall and footwall of Tertiary thrust faults (Fig. 2). Restoration of one of these detachment faults along the Lugu traverse, between Gangma Co and Lugu (Fig. 2), provided an estimate of ~28 km (~22% over 99 km) Tertiary shortening (Kapp et al., 2003b). Hanging-wall cutoffs are lacking for other thrust faults in the Qiangtang terrane, hindering accurate estimates of shortening. Mapped stratigraphic separations across the thrust faults suggest relatively minor structural throw (generally less than ~2–3 km). We estimate that ~25% shortening could produce the observed stratigraphic separations across the thrust faults and folding of Tertiary strata within their footwall. The possibility that major additional Tertiary shortening occurred along thrust flats deserves further consideration; however, there is no evidence at present, such as major thrust nappes or footwall duplexes, to support this.

Bangong Suture

Between Gaize and Siling Co (Fig. 2), the Bangong suture is modified by a system of mainly north-dipping, south-directed thrust faults that repeat Jurassic rocks in the hanging wall and involve Cretaceous-Tertiary (?) strata in the footwall (Fig. 7G). Although its initiation age is not known, the thrust system was demonstrably active during the Tertiary. Southeast of Gaize (~12 km), ~100 m of volcanic tuff lies above a slight angular unconformity with mid-Cretaceous red beds below (Figs. 5 and 7H). The tuff is folded into a broad northwest-trending syncline and is cut to the north by a north-dipping thrust. Biotite from a sample of the tuff (6-8-98-3; Figs. 2 and 5) yields a weighted mean $^{40}Ar/^{39}Ar$ plateau date of 64 ± 1 Ma over 60% ^{39}Ar released (Fig. 3K), which we interpret to be the age of volcanism. These relations demonstrate that shortening in the Gaize area occurred both prior to and during Cenozoic time. Northwest of Siling Co (southeasternmost part of Fig. 2), red beds and overlying dacitic tuffs crop out in the footwall of a north-dipping thrust fault with Permian limestone in the hanging wall. Biotite from a tuff sample (7-27-98-1; Fig. 2) yields a weighted mean $^{40}Ar/^{39}Ar$ plateau date of 42.7 ± 0.9 Ma (Fig. 3L), providing a minimum age for the red beds and evidence for post–middle Eocene shortening. In fact, Tertiary north-dipping thrust faults have modified the entire length of the Bangong suture in Tibet, from the Shiquanhe and Rutog areas in the west (Cheng and Xu, 1987; Matte et al., 1996; Kapp et al., 2003a) to the Lunpola and Amdo areas in the east (Yu and Zheng, 1979; Coward et al., 1988; Kidd et al., 1988; Guo et al., 2002; Wu et al., 2004) (Fig. 2), and are collectively referred to as the Shiquanhe-Gaize-Amdo thrust system (Yin and Harrison, 2000).

The Bangong suture is bounded on its southern margin by a south-dipping, north-directed thrust that can be traced continuously between Gaize and Siling Co (Fig. 2) and is here named the Gaize–Siling Co backthrust. The backthrust juxtaposes Lhasa terrane rocks in the hanging wall, which mostly consist of massive ridge-forming Aptian-Albian limestone, against Jurassic and mid-Cretaceous–Tertiary rocks in the footwall. No rocks of Lhasa terrane affinity, including mid-Cretaceous marine strata, were observed to crop out north of the backthrust in central Tibet. The Gaize–Siling Co backthrust is likely the youngest thrust along the Bangong suture because (1) it locally cuts the north–dipping Shiquanhe-Gaize-Amdo thrust system, and (2) hanging-wall Cretaceous limestone is the dominant source for southerly derived clasts in the youngest mapped Tertiary conglomerate unit (Tc), which buries the Southern Qiangtang thrust (Figs. 2, 5, and 6). Furthermore, a history of south-directed thrusting along the Bangong suture followed by north-directed thrusting in the south explains why the backthrust locally juxtaposes younger on older rocks (Figs. 2, 5, and 6). Thus, the Tertiary structure of the Bangong suture is reminiscent of that of the Indus-Yarlung suture to the south, having been modified by a south-directed thrust system (Gangdese thrust system) and a younger cross-cutting backthrust to the south (Great Counter Thrust) during the Indo-Asian collision (e.g., Yin et al., 1994; Yin et al., 1999a; Harrison et al., 2000).

The magnitude of post–mid-Cretaceous shortening across the Bangong suture is significant. In the Gaize area, a minimum of ~41 km shortening (47% over 46 km) is required to restore mid-Cretaceous strata to horizontal, under the assumptions that thrust faults root into a décollement at shallow depth and Jurassic suture zone rocks thickened homogeneously above the décollement (Fig. 5). Cretaceous-Tertiary (?) strata are estimated to have been shortened by a minimum of 16 km over 21.8 km (>42%) in the Nyima area (Fig. 6). These are minimum shortening estimates because hanging-wall cutoffs have been eroded and the only slip accounted for on the Gaize–Siling Co backthrust is that required to bury footwall rocks. Although thrusting along the Bangong suture occurred during the Tertiary, the initiation age of thrusting and hence the magnitude of Late Cretaceous versus Tertiary shortening is poorly known.

DISCUSSION

Tectonic Evolution of the Qiangtang and Lhasa Terranes

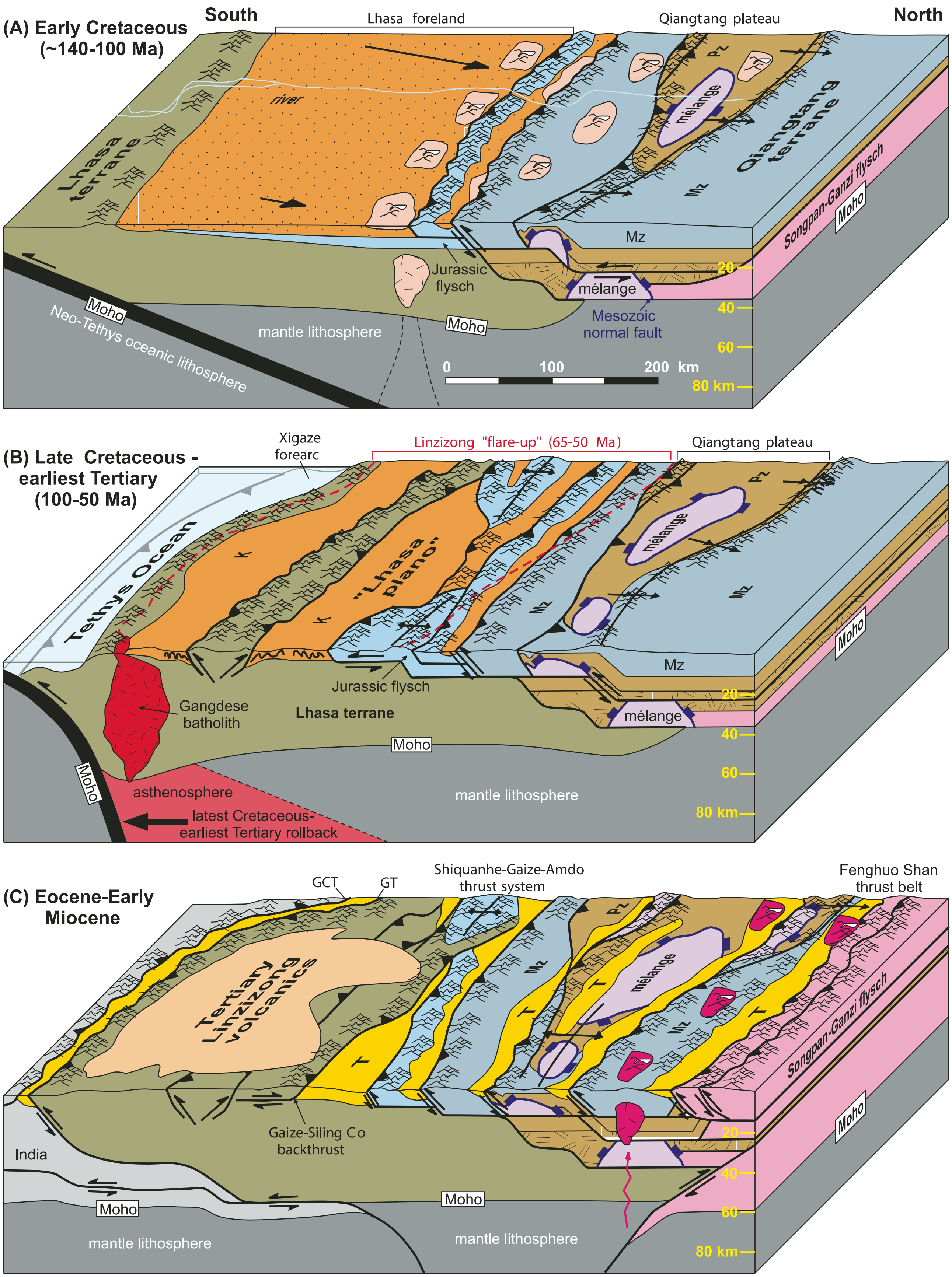
A comprehensive tectonic model for Tibetan plateau growth must explain (1) major denudation before and minor denudation since mid-Cretaceous time in the Qiangtang terrane, (2) mid-Cretaceous, earliest Tertiary, and middle Eocene–early Oligocene volcanism in central Tibet, (3) mid-Cretaceous nonmarine basin development and localization of Cretaceous-Tertiary shortening along the Bangong suture, and (4) widely distributed south-directed thrusting of Tertiary age within the Qiangtang terrane. As for the Lhasa terrane, major features that must be explained include: (1) major Cretaceous subsidence and basin infilling, (2) Early to mid-Cretaceous magmatism in the northern Lhasa terrane, (3) significant Cretaceous–earliest Tertiary and minimal post–earliest Tertiary upper-crustal shortening, and (4) extensive Paleocene-Eocene volcanism (Fig. 1). In the following, we present a new tectonic model for the Cretaceous-Tertiary history of magmatism, deformation, and basin development in the Qiangtang and Lhasa terranes (Fig. 8).

Early Cretaceous

The Lhasa terrane may have underthrust a significant distance northward beneath the Qiangtang terrane along the Bangong suture during Early Cretaceous time, following closure of the Bangong Ocean. Jurassic strata of the Bangong suture were likely deposited initially on transitional or oceanic basement. However, the suture must have been above sea level prior to mid-Cretaceous nonmarine basin development along it, requiring replacement of the original basement with underthrust continental crust. The restored length of Jurassic suture zone rocks near Gaize (Fig. 5; ~87 km) provides a minimum estimate for the magnitude of pre–mid-Cretaceous underthrusting. South-directed obduction of Bangong suture zone rocks (Girardeau et al., 1984, 1985; Coward et al., 1988; Kapp et al., 2003a) suggests that this underthrust crust is comprised of the northern Lhasa terrane margin (Figs. 5 and 8A).

Following Yin and Harrison (2000), we infer that upper Paleozoic strata and structurally underlying early Mesozoic mélange in the central Qiangtang terrane comprise a thrust sheet that was displaced southward over a north-dipping thrust ramp. As these rocks moved up and over the thrust ramp, the thrust sheet was deformed into a hanging-wall ramp anticlinorium, bounded by a monocline located above the thrust ramp to the north (inferred present position is along the contact between upper Paleozoic and Mesozoic strata in the northern Qiangtang terrane; Fig. 1) and the Lugu-Rongma thrust system in the south (Figs. 2 and 8A). This kinematic model is similar to that which has been proposed to explain culminations in many other fold-thrust belts worldwide (e.g., Rich, 1934; Price, 1981; Boyer and Elliott, 1982). The ramp anticline model predicts that the width of the Qiangtang anticlinorium grew in a north-south direction with time and provides a minimum estimate of shortening. In the western Qiangtang terrane, the distance between the Lugu thrust system and the monocline to the north is ~150 km (Fig. 2). Along the Rongma traverse, mid-Cretaceous volcanic rocks lie unconformably on Carboniferous strata, ~75 km north of the Lugu-Rongma thrust system (Fig. 2). This relationship suggests that, in this area, at least half of the slip required to produce the Qiangtang anticlinorium occurred prior to mid-Cretaceous volcanism (Fig. 8A). The anticlinorium is east plunging and its north-south width decreases eastward, where it is ~90 km wide along the Rongma traverse and not definable based on regional geologic map patterns east of Shuang Hu (Fig. 1). These relations imply an eastward decrease in both thrust sheet displacement and structural relief on the thrust ramp. Interestingly, the north-south width of the Lhasa terrane increases eastward, being more than 100 km wider at the longitude of Shuang Hu than in westernmost Tibet (Fig. 3). This correlation is consistent with our interpretation that growth of the Qiangtang anticlinorium is kinematically linked with Lhasa terrane underthrusting, with clockwise rotation of the underthrusting Lhasa terrane explaining the larger magnitude of underthrusting in the west than in the east (Fig. 8A). Alternatively, if the correlation between the eastward decrease in the width of the Qiangtang anticlinorium and the eastward increase in the width of the Lhasa terrane is coincidental, an original irregular margin configuration for the Lhasa terrane (having a promontory in the west) is suggested.

Northward low-angle subduction of Neo-Tethyan oceanic lithosphere along the Indus-Yarlung suture may have provided the driving mechanism for continental underthrusting (Fig. 8A) and can explain the presence of Early Cretaceous granites in the northern Lhasa terrane (Fig. 1) (Coulon et al., 1986). Subsurface loading by the excess weight of the underthrusting oceanic lithosphere (Bird, 1984) and topographic loading by the overthrusting Qiangtang terrane could have produced a broad peripheral foreland basin in the Lhasa terrane. Sediments shed from the growing Qiangtang anticlinorium could have in large part filled this basin and


(A) Early Cretaceous (~140-100 Ma)
South
Lhasa foreland
Qiangtang plateau
North
Lhasa terrane
river
mélange
Qiangtang terrane
Pz
Mz
Songpan-Ganzi flysch
Moho
Jurassic flysch
mélange
Mesozoic normal fault
Neo-Tethys oceanic lithosphere
mantle lithosphere
0
100
200 km
20
40
60
80 km
(B) Late Cretaceous - earliest Tertiary (100-50 Ma)
Xigaze forearc
Linzizong "flare-up" (65-50 Ma)
Qiangtang plateau
Tethys Ocean
K
"Lhasa plano"
mélange
Pz
Mz
Jurassic flysch
Gangdese batholith
Lhasa terrane
Moho
asthenosphere
latest Cretaceous-earliest Tertiary rollback
mantle lithosphere
20
40
60
80 km
(C) Eocene-Early Miocene
GCT
GT
Shiquanhe-Gaize-Amdo thrust system
Fenghuo Shan thrust belt
Tertiary Linzizong volcanics
T
Pz
Mz
mélange
Songpan-Ganzi flysch
Moho
Gaize-Siling Co backthrust
India
mantle lithosphere
20
40
60
80 km

may have been transported to as far south as the Xigaze forearc (shown in Fig. 8B) (Dürr et al., 1995; Dürr, 1996). Mid-Cretaceous red beds along the Bangong suture may have been deposited in basins that developed on top of active thrust sheets along the Bangong suture (wedge-top basins; DeCelles and Giles, 1996). Early Cretaceous northward underthrusting of the Lhasa terrane and growth of the Qiangtang anticlinorium could have produced an elevated and relatively low-relief plateau in central Tibet (Fig. 8A), as large areas of the Qiangtang terrane have been above sea level and experienced minimal denudation since mid-Cretaceous time.

Late Cretaceous–Earliest Tertiary

The Lhasa terrane underwent major upper crustal shortening (>40%) during Late Cretaceous–earliest Tertiary time, as indicated by fold-thrust development in the Shiquanhe-Rutog area (Fig. 1) and deformation of Upper Cretaceous strata in southern Tibet prior to earliest Tertiary volcanism (Burg and Chen, 1984; Pan, 1993; Ratschbacher et al., 1994; Matte et al., 1996; Murphy et al., 1997; Ding and Lai, 2003; Kapp et al., 2003a). This shortening may have been accommodated in the deeper Lhasa terrane crust by continued northward underthrusting beneath the Qiangtang terrane (Fig. 8B) (Kapp et al., 2003a). Northward growth of the Qiangtang anticlinorium may have continued also, as Qiangtang terrane basement was pushed beneath it by the underthrusting Lhasa terrane (Fig. 8B). During latest Cretaceous–earliest Tertiary time, the previously low-angle-subducting Tethyan oceanic lithosphere may have rolled back and resulted in the voluminous and widespread Linzizong volcanic "flare-up" and the development of the Andean-style Gangdese arc in the southernmost Lhasa terrane (Ding et al., 2003) (Fig. 8B). A contractional setting would have been maintained in southern Tibet during slab rollback in the likely case that extremely rapid convergence of the Indian plate at this time (100–170 mm/yr; e.g., Lee and Lawver, 1995) exceeded the rate of Neo-Tethyan oceanic subduction. Early Cretaceous low-angle subduction of Tethyan oceanic lithosphere followed by earliest Tertiary slab rollback could have removed significant parts of continental mantle lithosphere beneath the Lhasa terrane before the Indo-Asian collision, which in turn may have facilitated India's underthrusting beneath southern Tibet during the Cenozoic (Ding et al., 2003).

Eocene–Early Miocene

Under the assumption that Tertiary basin development in the Qiangtang terrane was controlled by thrusting, the Eocene-Oligocene ages of interbedded volcanic tuffs provide an estimate for the timing of shortening. The Qiangtang terrane deeper crust is inferred to include large volumes of mélange and flysch that were underthrust from the Jinsha suture to the north (Fig. 1) during early Mesozoic time (Kapp et al., 2000; Kapp et al., 2003b). These relatively weak materials in the deeper central Tibetan crust may help explain why Tertiary upper crustal shortening was more widely distributed and prevalent in the Qiangtang terrane than in the Lhasa terrane. Along the Rongma traverse, we suggest that large-wavelength Tertiary folding near Rongma (Fig. 2) amplified a preexisting hanging-wall ramp anticline that formed during Cretaceous emplacement of the inferred upper Paleozoic strata–mélange thrust sheet (Fig. 8C). Tertiary shortening by amplification of a preexisting anticline as opposed to initiation of new thrust faults could be explained by the presence of mélange in the upper crust, which may have been weaker and more favorable to internal deformation than upper Paleozoic strata to the north and south. Modification of the northern limb of a preexisting ramp anticline by the Gangma Co–Shuang Hu thrust system can explain why the thrust system locally places younger on top of older rocks (Figs. 2 and 8C). It is possible that Tertiary thrust faults in the Qiangtang terrane and along the Bangong suture rooted into the décollement beneath the Cretaceous thrust sheet and fed additional slip to the north-dipping midcrustal thrust ramp in the northern Qiangtang terrane (Fig. 8C). Thick sections (up to 5 km) of Paleocene to Oligocene nonmarine strata exposed along the Bangong suture near Lunpola (Fig. 1) (Yu and Zheng, 1979; Ai et al., 1998; Luo et al., 1996) may be remnants of a foreland basin system that developed due to regional flexural subsidence as the Qiangtang terrane overthrust the Lhasa terrane. Whereas Eocene-Oligocene volcanic tuffs are locally interbedded with or overlie red beds in the central and southern Qiangtang terrane, volcanic centers and intrusive rocks of this age are restricted to the northern Qiangtang terrane (Fig. 1). Following previous workers (Roger et al., 2000; Tapponnier et al., 2001; Wang et al., 2001; Ding et al., 2003; Spurlin et al., 2005), we attribute this magmatism to southward continental subduction of the Songpan-Ganzi flysch complex along the Jinsha suture, which was reactivated by the early Tertiary Fenghuo Shan–Hoh Xil thrust system (Fig. 8C). Potentially significant northward underthrusting of the Lhasa terrane along the Bangong suture may have occurred at too gentle of an angle to initiate partial melting of the mantle during the Tertiary.

Implications for Crustal Thickening

Our model for the tectonic evolution of southern and central Tibet implies that significant crustal thickening began in central Tibet no later than mid-Cretaceous time and extended southward to the Lhasa terrane during Late Cretaceous–earliest Tertiary time (Fig. 8). Recent studies indicate that significant Cretaceous–earliest Tertiary crustal thickening extended to the west in the Hindu Kush, Karakoram, and Pamir (Fraser et al., 2001; Hildebrand et al., 2001; Robinson et al., 2004) and to the east in the Longmen Shan (Wallis et al., 2003). Models of Tibetan plateau formation and collisional orogeny in Asia need to consider the growing evidence that large parts of the southern Asian continental margin were substantially thickened prior to Indo-Asian collision.

We propose that the dominant mechanism of crustal thickening in central Tibet was by northward low-angle underthrusting of Lhasa terrane lithosphere beneath the Qiangtang terrane, analogous to underthrusting of India beneath southern Tibet during the Cenozoic. Specific

Figure 8. Proposed tectonic evolution of the Lhasa and Qiangtang terranes during Cretaceous-Tertiary time. (A) Early Cretaceous growth of the Qiangtang anticlinorium may have occurred by southward emplacement of a thrust sheet over a midcrustal ramp. Deformation, basin development, and magmatism are attributed to northward underthrusting of the Lhasa terrane beneath the Qiangtang terrane along the Bangong suture during northward low-angle subduction of Neo-Tethys oceanic lithosphere. Mz—Mesozoic Strata; Pz—Paleozoic Strata. (B) Late Cretaceous–earliest Tertiary southward propagation of upper crustal shortening and continued northward underthrusting of the Lhasa terrane beneath the Qiangtang terrane. Rollback of Neo-Tethys oceanic lithosphere resulted in the development of an Andean-style margin in southern Tibet. K—Cretaceous Strata. (C) Cenozoic insertion of India into a previously thickened Tibetan crust was accommodated by additional northward underthrusting of the Lhasa terrane beneath the Qiangtang terrane along the Bangong suture and southward continental subduction along the Jinsha suture. GCT—Great Counter thrust; GT—Gangdese thrust system; T—Tertiary nonmarine strata; Moho—crust-mantle boundary.

crustal thickness estimates for the Qiangtang and Lhasa terranes are precluded because of the uncertainty in the extent to which the Lhasa terrane basement accommodated shortening by northward underthrusting or internal thickening. However, recent studies allow first-order minimum estimates of bulk upper crustal shortening in the Qiangtang and Lhasa terranes. Based on 40% pre–earliest Tertiary shortening of the Cretaceous Takena Formation near Lhasa (Pan, 1993), we assume that the southernmost 75 km of the Lhasa terrane was shortened 50 km during Late Cretaceous–earliest Tertiary time. To the west, near Coqin, the central Lhasa terrane was shortened 187 km over a present-day north-south distance of 132 km (~59%) during the Cretaceous (Murphy et al., 1997). It is estimated that the northern Lhasa terrane in westernmost Tibet was shortened >60 km over a present-day north-south distance of 50 km (~55%) during the Late Cretaceous–early Tertiary, with the bulk of shortening being latest Cretaceous in age (Kapp et al., 2003a). For west-central Tibet, we infer (1) >41 km of post–mid-Cretaceous shortening across the present-day 46-km-wide Bangong suture zone near Gaize (~47%), (2) >75 km of Cretaceous shortening along the inferred Paleozoic–mélange thrust sheet (Fig. 8A), and (3) a conservative minimum estimate of 25% Tertiary shortening (~57 km) across the present-day 170 km width of the Qiangtang terrane studied (Fig. 2). Taking the above estimates together, the Lhasa and Qiangtang terranes were shortened >470 km over a present-day distance of 473 km (>50%) and mainly prior to Indo-Asian collision. Under the assumptions that the Lhasa and Qiangtang terranes were characterized by a 35-km-thick crust prior to shortening and conservation of crustal volume, this shortening could have produced an average crustal thickness of >70 km. Taking Cretaceous and younger denudation into account would decrease this estimate, but probably by no more than 10 km based on widely preserved low-grade Cretaceous strata in the Lhasa terrane and along the Bangong suture and pre-Cretaceous $^{40}Ar/^{39}Ar$ mica cooling ages in the Qiangtang terrane (Kapp et al., 2000; Kapp et al., 2003b; this study). A thick crust in southern and central Tibet prior to Indo-Asian collision suggests that the ~700-km-long slab of Indian basement that underthrust the Himalaya (DeCelles et al., 2002) was accommodated by northward underthrusting and subduction of Tibetan continental crust (as shown for early Tertiary time; Fig. 8C) (Yin and Harrison, 2000; Tapponnier et al., 2001), flow of Tibetan deeper crust to the east to thicken the eastern margin of the Tibetan plateau (likely during Miocene to recent time; Royden et al., 1997; DeCelles et al., 2002), and/or delamination of lower crust (e.g., Le Pichon et al., 1997).

CONCLUSIONS

Preservation of a gently dipping angular unconformity beneath mid-Cretaceous volcanic flows and tuffs in the Qiangtang terrane demonstrates that parts of central Tibet were above sea level during and experienced major shortening and denudation prior to mid-Cretaceous time. Southward emplacement of an inferred thrust sheet of upper Paleozoic strata and early Mesozoic mélange in the central Qiangtang terrane initiated prior to mid-Cretaceous volcanism and likely during Early Cretaceous Lhasa-Qiangtang collision. The Bangong suture was characterized by volcanism and nonmarine basin development during mid-Cretaceous time. Tertiary deformation in central Tibet is characterized by mainly north-dipping thrust systems with Eocene-Oligocene red beds and volcanic rocks in the footwall. The Tertiary Gaize–Siling Co backthrust defines the surface expression of the southern boundary of the Bangong suture and the northernmost extent of mid-Cretaceous marine strata in central Tibet. Cretaceous shortening, basin development, and magmatism in central Tibet are attributed to northward underthrusting of the Lhasa terrane beneath the Qiangtang terrane along the Bangong suture during low-angle subduction of Neo-Tethys oceanic lithosphere. This model implies substantial crustal thickening and perhaps plateau formation in central Tibet prior to the Indo-Asian collision. Tertiary shortening and basin development in central Tibet may record continued Lhasa terrane underthrusting along the Bangong suture, which may have both accommodated and been driven by insertion of Indian basement into a previously thickened Tibetan crust.

ACKNOWLEDGMENTS

This research was supported by the U.S. National Science Foundation grant (EAR-98-05340) awarded to A. Yin and T.M. Harrison, Geological Society of America and American Association of Petroleum Geologists student grants awarded to P. Kapp, and a Chinese National Key Project grant (1998040800) awarded to L. Ding. We thank Matthew Spurlin, Michael Taylor, Jessica Kapp, Zhou Yong, and Deng Xi-Guang for assistance with the field work and Marty Grove and Eric Cowgill for assistance with $^{40}Ar/^{39}Ar$ data collection. This manuscript benefited from comments on an early draft by Brian Darby, Peter DeCelles, Brian Horton, Michael Murphy, Peter Bird, and John Volkmer, and reviews by Jeff Amato, Clark Burchfiel, Michael Edwards, John Geissman, Richard Law, and Mike Searle.

REFERENCES CITED

Ai, H., Lan, L., Zhu, H., Zhang, K., and Zhen, T., 1998, The forming mechanism and petroleum geology of Tertiary Lunpola basin, southwest China: Acta Petrolei Sinica, v. 19, p. 21–27.

Allègre, C.J., Courtillot, V., Tapponier, P., Him, A., Mattauer, M., Coulon, C., Jaeger, J.J., Achache, J., Schaerer, U., Marcoux, J., Burg, J.P., Girardeau, J., Armijo, R., Gariepy, C., Coepel, C., Li, T., Xiao, X., Chang, C., Li, G., Lin, B., Teng, J.W., Wang, N., Chen, G., Han, T., Wang,X., Den, W., Sheng, H., Cao, Y., Zhou, J., Qui, H., Bao, P., Wang, S., Wang, B., Zhou, Y., and Ronghua, X., 1984, Structure and evolution of the Himalaya-Tibet orogenic belt: Nature, v. 307, p. 17–22.

Bird, P., 1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: Tectonics, v. 3, p. 741–758.

Boyer, S.E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196–1230.

Burg, J.-P., and Chen, G.M., 1984, Tectonics and structural zonation of southern Tibet, China: Nature, v. 311, p. 219–223.

Burg, J.-P., Proust, F., Tapponnier, P., and Chen, G.M., 1983, Deformation phases and tectonic evolution of the Lhasa block (Southern Tibet, China): Eclogae geologica Helvetica, v. 76, p. 643–665.

Cheng, J., and Xu, G., 1986, Geologic map of the Gaize region with report: Chengdu, Tibetan Bureau of Geology and Mineral Resources, 369 p., scale 1:1,000,000.

Cheng, J., and Xu, G., 1987, Geologic Map of the Ritu Region with report: Chengdu, Tibetan Bureau of Geology and Mineral Resources, 598 p., scale 1:1,000,000.

Chung, S.-L., Lo, C.-H., Lee, T.-Y., Zhang, Y., Xie, Y., Li, X., Wang, K.-L., and Wang, P.-L., 1998, Diachronous uplift of the Tibetan plateau starting 40 Myr ago: Nature, v. 394, p. 769–773.

Clark, M.K., and Royden, L.H., 2000, Topographic ooze: Building the eastern margin of Tibet by lower crustal flow: Geology, v. 28, p. 703–706.

Coulon, C., Maluski, H., Bollinger, C., and Wang, S., 1986, Mesozoic and Cenozoic volcanic rocks from central and southern Tibet: ^{39}Ar-^{40}Ar dating, petrological characteristics and geodynamical significance: Earth and Planetary Science Letters, v. 79, p. 281–302.

Coward, M.P., Kidd, W.S.F., Pan, Y., Shackleton, R.M., and Zhang, H., 1988, The structure of the 1985 Tibet Geotraverse, Lhasa to Golmud: Philosophical Transactions of the Royal Society of London, Series A, v. 327, p. 307–336.

D'Andrea, J., Harrison, T.M., Grove, M., and Xinhua, Z., 1999, The thermal and physical state of the south Tibetan middle crust between 20–8 Ma: U-Th-Pb and Nd isotopic evidence from the Nyainqentanglha massif, *in* Sobel, E., Appel, E., Strecker, M., Ratschbacher, L., and Blisniuk, P., eds., 14th Himalaya-Karakoram-Tibet Workshop: Kloster Ettal, Germany, p. 29.

Debon, F., Le Fort, P., Sheppard, S.M., and Sonet, J., 1986, The four plutonic belts of the Transhimalaya-Himalaya: A chemical, mineralogical, isotopic, and chronological synthesis along a Tibet-Nepal section: Journal of Petrology, v. 27, p. 219–250.

DeCelles, P.G., and Giles, K.A., 1996, Foreland basin systems: Basin Research, v. 8, p. 105–123.

DeCelles, P.G., Robinson, D.M., and Zandt, G., 2002, Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau: Tectonics, v. 21, p. 1062.

Deng, W.M., 1989, Volcanism in Tibet: Journal of Natural Resources, v. 3, p. 205–210.

Deng, W.M., Sun, H.J., and Zhang, Y.Q., 2000, K-Ar age of the Cenozoic volcanic rocks in the Nangqen Basin, Qinghai Province and its geological significance: Chinese Science Bulletin, v. 45, p. 1015–1019.

Dewey, J.F., and Bird, J.M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Ding, L., and Lai, Q., 2003, New geological evidence of crustal thickening in the Gangdese block prior to the Indo-Asian collision: Chinese Science Bulletin, v. 48, p. 1604–1610.

Ding, L., Kapp, P., Zhong, D., and Deng, W., 2003, Cenozoic volcanism in Tibet: Evidence for a transition from oceanic to continental subduction: Journal of Petrology, v. 44, p. 1833–1865.

Dürr, S.B., 1996, Provenance of Xigaze fore-arc basin clastic rocks (Cretaceous, south Tibet): Geological Society of America Bulletin, v. 108, p. 669–684.

Dürr, S.B., Ricken, W., and Einsele, G., 1995, Sedimentation and provenance patterns at an active plate margin: The Cretaceous Xigaze forearc basin (Tibet): Journal of Nepal Geological Society, v. 11, p. 1–15.

England, P., and Searle, M., 1986, The Cretaceous-Tertiary deformation of the Lhasa block and its implications for crustal thickening in Tibet: Tectonics, v. 5, p. 1–14.

Fielding, E.J., 1996, Tibet uplift and erosion: Tectonophysics, v. 260, p. 55–84.

Fraser, J.E., Searle, M.P., Parrish, R.R., and Noble, S.R., 2001, Chronology of deformation, metamorphism, and magmatism in the southern Karakoram Mountains: Geological Society of America Bulletin, v. 113, p. 1443–1455.

Girardeau, J., Marcoux, J., Allègre, C.J., Bassoullet, J.P., Youking, T., Xuchang, X., Yougong, Z., and Xibin, W., 1984, Tectonic environment and geodynamic significance of the Neo-Cimmerian Donqiao ophiolite, Bangong-Nujiang suture zone, Tibet: Nature, v. 307, p. 27–31.

Girardeau, J., Marcoux, J., Fourcade, E., Bassoullet, J.P., and Youking, T., 1985, Xainxa ultramafic rocks, central Tibet, China: Tectonic environment and geodynamic significance: Geology, v. 13, p. 330–333.

Guo, J., Brown, L., Gonsalves, C., Pananont, P., and Jordan, T., 2002, Evolution of the Lunpola-Duba basin complex, central Tibet, from reprocessed seismic data of the China National Star Petroleum Company: Geological Society of America, Abstracts with Programs, v. 34, no. 6, p. 486.

Hacker, B.R., Gnos, E., Ratschbacher, L., Grove, M., McWilliams, M., Sobolev, S.V., Wan, J., and Zhenhan, W., 2000, Hot and dry deep crustal xenoliths from Tibet: Science, v. 287, p. 2463–2466.

Harris, N.B.W., Inger, S., and Ronghua, X., 1990, Cretaceous plutonism in Central Tibet: An example of post-collision magmatism?: Journal of Volcanology and Geothermal Research, v. 44, p. 21–32.

Harrison, T.M., Yin, A., Grove, M., Lovera, O.M., Ryerson, F.J., and Zhou, X., 2000, The Zedong Window: A record of superposed Tertiary convergence in southeastern Tibet: Journal of Geophysical Research, v. 105, p. 19,211–19,230.

He, S., Leier, A., and Kapp, P., 2003, Upper crustal deformation in southern Tibet before and during the Indo-Asian collision: Geological Society of America, Abstracts with Programs, v. 34, no. 7, p. 30.

Hildebrand, P.R., Noble, S.R., Searle, M.P., Waters, D.J., and Parrish, R.R., 2001, Old origin for an active mountain range: Geology and geochronology of the eastern Hindu Kush, Pakistan: Geological Society of America Bulletin, v. 113, p. 625–639.

Hodges, K.V., Hurtado, J.M., and Whipple, K.X., 2001, Southward extrusion of Tibetan crust and its effect on Himalayan tectonics: Tectonics, v. 20, p. 799–809.

Horton, B.K., Yin, A., Spurlin, M.S., Zhou, J., and Wang, J., 2002, Paleocene-Eocene syncontractional sedimentation in narrow, lacustrine-dominated basins of east-central Tibet: Geological Society of America Bulletin, v. 114, p. 771–786.

Kapp, P., Yin, A., Manning, C.E., Murphy, M., Harrison, T.M., Spurlin, M., Ding, L., Deng, X.-G., and Wu, C.-M., 2000, Blueschist-bearing metamorphic core complexes in the Qiangtang block reveal deep crustal structure of northern Tibet: Geology, v. 28, p. 19–22.

Kapp, P., Murphy, M.A., Yin, A., Harrison, T.M., Ding, L., and Guo, J., 2003a, Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet: Tectonics, v. 22, p. 1029.

Kapp, P., Yin, A., Manning, C.E., Harrison, T.M., Taylor, M.H., and Ding, L., 2003b, Tectonic evolution of the early Mesozoic blueschist-bearing Qiangtang metamorphic belt, central Tibet: Tectonics, v. 22, p. 1043.

Kidd, W.S.F., Pan, Y., Chang, C., Coward, M.P., Dewey, J.F., Gansser, A., Molnar, P., Shackleton, R.M., and Sun, Y., 1988, Geological mapping of the 1985 Chinese-British Tibetan (Xizang-Qinghai) Plateau Geotraverse route: Philosophical Transactions of the Royal Society of London, Series A, v. 327, p. 287–305.

Kind, R., Yuan, X., Saul, J., Nelson, D., Sobolev, S.V., Mechie, J., Zhao, W., Kosarev, G., Ni, J., Achauer, U., and Jiang, M., 2002, Seismic images of crust and upper mantle beneath Tibet: Evidence for Eurasian plate subduction: Science, v. 298, p. 1219–1221.

Kong, X., Yin, A., and Harrison, T.M., 1997, Evaluating the role of preexisting weaknesses and topographic distributions in the Indo-Asian collision by use of a thin-shell numerical model: Geology, v. 25, p. 527–530.

Lee, T.-Y., and Lawver, L.A., 1995, Cenozoic plate reconstruction of Southeast Asia: Tectonophysics, v. 251, p. 85–138.

Leeder, M.R., Smith, A.B., and Jixiang, Y., 1988, Sedimentology and palaeoenvironmental evolution of the 1985 Lhasa to Golmud geotraverse: Philosophical Transactions of the Royal Society of London, Series A, v. 327, p. 107–143.

Leier, A.L., He, S., Kapp, P., and Ding, L., 2002, Jurassic-Cretaceous deposits of the central Lhasa terrane: Implications for the tectonic evolution of southern Asia prior to the Indo-Asian collision: Geological Society of America, Abstracts with Programs, v. 34, no. 6, p. 412.

Le Pichon, X., Henry, P., and Goffe, B., 1997, Uplift of Tibet: From eclogites to granulites—Implications for the Andean Plateau and the Variscan belt: Tectonophysics, v. 273, p. 57–76.

Li, C., and Zheng, A., 1993, Paleozoic stratigraphy in the Qiangtang region of Tibet: Relations of the Gondwana and Yangtze continents and ocean closure near the end of the Carboniferous: International Geology Review, v. 35, p. 797–804.

Li, C., Liren, C., Ke, H., Zengrong, Y., and Yurong, H., 1995, Study on the paleo-Tethys suture zone of Lungmu Co-Shuanghu, Tibet: Beijing, Geological Publishing House, 131 p.

Liu, Z., and Wang, C., 2001, Facies analysis and depositional systems of Cenozoic sediments in the Hoh Xil basin, northern Tibet: Sedimentary Geology, v. 140, p. 251–270.

Liu, Z., Wang, C., and Yi, H., 2001, Evolution and mass accumulation of the Cenozoic Hoh Xil basin, northern Tibet: Journal of Sedimentary Research, v. 71, p. 971–984.

Liu, Z.Q.C., 1988, Geologic Map of the Qinghai-Xizang Plateau and its Neighboring Regions: Chengdu Institute of Geology and Mineral Resources, Geologic Publishing House, Beijing, scale 1:1,500,000.

Luo, B., Dai, G., and Pan, Z., 1996, Oil and gas potential in Paleogene terrestrial Bangonghu-Dinging suture zone: Journal of China University of Geosciences, v. 21, p. 163–167.

Maluski, H., Proust, F., and Xiao, X.C., 1982, $^{39}Ar/^{40}Ar$ dating of the trans-Himalayan calc-alkaline magmatism of southern Tibet: Nature, v. 298, p. 152–154.

Matte, P., Tapponnier, P., Arnaud, N., Bourjot, L., Avouac, J.P., Vidal, P., Liu, Q., Pan, Y., and Wang, Y., 1996, Tectonics of Western Tibet, between the Tarim and the Indus: Earth and Planetary Science Letters, v. 142, p. 311–330.

McDougall, I., and Harrison, T.M., 1999, Geochronology and Thermochronology by the $^{40}Ar/^{39}Ar$ Method: New York, Oxford University Press, 2nd edition, 269 p.

Miller, C., Schuster, R., Klotzli, U., Frank, W., and Purtscheller, F., 1999, Post-collisional potassic and ultrapotassic magmatism in SW Tibet: Geochemical and Sr-Nd-Pb-O isotopic constraints for mantle source characteristics and petrogenesis: Journal of Petrology, v. 40, p. 1399–1424.

Miller, C., Schuster, R., Klotzli, U., Frank, W., and Grasemann, B., 2000, Late Cretaceous-Tertiary magmatic and tectonic events in the Transhimalaya batholith (Kailas area, SW Tibet): Schweizerische Mineralogische und Petrographische Mitteilungen, v. 80, p. 1–20.

Murphy, M.A., Yin, A., Harrison, T.M., Dürr, S.B., Chen, Z., Ryerson, F.J., Kidd, W.S.F., Wang, X., and Zhou, X., 1997, Did the Indo-Asian collision alone create the Tibetan plateau?: Geology, v. 25, p. 719–722.

Nelson, K.D., Zhao, W., Brown, L.D., Kuo, J., Che, J., Liu, X., Klemperer, S.L., Makovsky, Y., Meissner, R., Mechie, J., Kind, R., Wenzel, F., Ni, J., Nabelek, J., Chen, L., Tan, H., Wei, W., Jones, A.G., Booker, J., Unsworth, M., Kidd, W.S.F., Hauck, M., Alsdorf, D., Ross, A., Cogan, M., Wu, C., Sandvol, E., and Edwards, M., 1996, Partially molten middle crust beneath southern Tibet: Synthesis of Project INDEPTH results: Nature, v. 274, p. 1684–1688.

Owens, T.J., and Zandt, G., 1997, Implications of crustal property variations for models of Tibetan plateau evolution: Nature, v. 387, p. 37–43.

Pan, Y., 1993, Unroofing history and structural evolution of the southern Lhasa terrane, Tibetan Plateau: Implications for the continental collision between India and Asia [Ph.D. thesis]: Albany, State University of New York, 287 p.

Pearce, J.A., and Deng, W., 1988, The ophiolites of the Tibetan Geotraverses, Lhasa to Golmud (1985) and Lhasa to Kathmandu (1986): Philosophical Transactions of the Royal Society of London, Series A, v. 327, p. 215–238.

Pearce, J.A., and Mei, H., 1988, Volcanic rocks of the 1985 Tibet Geotraverse: Lhasa to Golmud: Philosophical Transactions of the Royal Society of London, Series A, v. 327, p. 169–201.

Price, R.A., 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, *in* McClay, K.R., and Price, N.J., eds., Thrust and Nappe Tectonics: London, Blackwell Scientific Publications, p. 427–448.

Ratschbacher, L., Frisch, W., Liu, G., and Chen, C.C., 1994, Distributed deformation in southern and western Tibet during and after the India-Asian collision: Journal of Geophysical Research, v. 99, p. 19,917–19,945.

Rich, J.L., 1934, Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky, and Tennessee: American Association of Petroleum Geologists Bulletin, v. 18, p. 1584–1596.

Robinson, A.C., Yin, A., Manning, C.E., Harrison, T.M., Zhang, S.-H., and Wang, X.-F., 2004, Tectonic evolution of the northeastern Pamir: Constraints from the northern portion of the Cenozoic Kongur Shan extensional system, western China: Geological Society of America Bulletin, v. 116, p. 953–973.

Roger, F., Tapponnier, P., Arnaud, N., Schärer, U., Brunel, M., Xu, Z., and Yang, J., 2000, An Eocene magmatic belt across central Tibet: Mantle subduction triggered by the Indian collision?: Terra Nova, v. 12, p. 102–108.

Ross, A.R., Brown, L.D., Pananont, P., Nelson, K.D., Klemperer, S., Haines, S., Zhao, W., and Guo, J., 2004, Deep reflection surveying in central Tibet: Lower-crustal layering and crustal flow: Geophysical Journal International, v. 156, p. 115–128.

Royden, L.H., Burchfiel, B.C., King, R.W., Erchie, W., Zhiliang, C., Feng, S., and Yuping, L., 1997, Surface deformation and lower crustal flow in eastern Tibet: Science, v. 276, p. 788–790.

Schneider, W., Mattern, F., Wang, P., and Li, C., 2003, Tectonic and sedimentary basin evolution of the eastern Bangong-Nujiang zone (Tibet): A Reading cycle: Geologische Rundschau, v. 92, p. 228–254.

Searle, M.P., Windley, B.F., Coward, M.P., Cooper, D.J.W., Rex, A.J., Li, T., Xiao, X., Jan, M.Q., Thakur, V.C., and Kumar, S., 1987, The closing of the Tethys and the tectonics of the Himalaya: Geological Society of America Bulletin, v. 98, p. 678–701.

Searle, M.P., Cooper, D.J.W., and Rex, A.J., 1988, Collision tectonics of the Ladakh-Zanskar Himalaya: Philosophical Transactions of the Royal Society of London, Series A, v. 326, p. 117–150.

Spurlin, M.S., Yin, A., Horton, B.K., Zhou, J., and Wang, J., 2005, Structural evolution of the Yushu-Nangqian region and its relationship to syn-collisional igneous activity east-central Tibet: Geological Society of America Bulletin, v. 117.

Tang, Y., and Wang, F., 1984, Primary analysis of the tectonic environment of the ophiolite in Northern Xizang: Himalayan Geology, v. 2, p. 99–113.

Tapponnier, P., Mercier, J.L., Proust, F., Andrieux, J., Armijo, R., Bassoullet, J.P., Brunel, M., Burg, J.P., Colchen, M., Dupre, M., Giradeau, J., Marcoux, J., Mascle, G., Matte, P., Nicolas, A., Li, T., Xiao, X., Chang, C., Lin, P., Li, G., Wan, N., Chen, G., Han, T., Wang, X.b., Den, W., Zheng, H., Sheng, H., Cao, Y., Zhou, J., and Qin, H., 1981, The Tibetan side of the India-Eurasia collision: Nature, v. 294, p. 405–410.

Tapponnier, P., Xu, Z., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., and Yang, J., 2001, Oblique stepwise rise and growth of the Tibet Plateau: Science, v. 294, p. 1671–1677.

Taylor, M., Yin, A., Ryerson, F.J., Kapp, P., and Ding, L., 2003, Conjugate strike-slip faulting along the Bangong-Nujiang suture zone accommodates coeval east-west extension and north-south shortening in the interior of the Tibetan Plateau: Tectonics, v. 22, p. 1044.

Wallis, S., Tsujimori, T., Aoya, M., Kawakami, T., Terada, K., Suzuki, K., and Hyodo, H., 2003, Cenozoic and Mesozoic metamorphism in the Longmenshan orogen: Implications for geodynamic models of eastern Tibet: Geology, v. 31, p. 745–748.
Wang, J.-H., Yin, A., Harrison, T.M., Grove, M., Zhang, Y.-Q., and Xie, G.-H., 2001, A tectonic model for Cenozoic igneous activities in the eastern Indo-Asian collision zone: Earth and Planetary Science Letters, v. 188, p. 123–133.
Wang, S., Li, Z., and Qiangba, X., 1983, Geologic map and report of the Xigaze area: Chengdu, Tibetan Bureau of Geology and Mineral Resources, 568 p, scale 1:l,000,000.
Wu, Z., Hu, D., Ye, P., Zhao, X., and Liu, Q., 2004, Thrusting of the North Lhasa Block in the Tibetan Plateau: Journal of the Geological Society of China, v. 78, p. 246–259.
Xu, R.-H., Schärer, U., and Allègre, C.J., 1985, Magmatism and metamorphism in the Lhasa block (Tibet): A geochronological study: Journal of Geology, v. 93, p. 41–57.
Yin, A., and Harrison, T.M., 2000, Geologic Evolution of the Himalayan-Tibetan Orogen: Annual Reviews of Earth and Planetary Science, v. 28, p. 211–280.
Yin, A., Harrison, T.M., Ryerson, F.J., Chen, W.J., Kidd, W.S.F., and Copeland, P., 1994, Tertiary structural evolution of the Gangdese thrust system in southeastern Tibet: Journal of Geophysical Research, v. 99, p. 18,175–18,201.
Yin, A., Harrison, T.M., Murphy, M.A., Grove, M., Nie, S., Ryerson, F.J., Wang, X.F., and Chen, Z.L., 1999a, Tertiary deformation history of southeastern and southwestern Tibet during the Indo-Asian collision: Geological Society of America Bulletin, v. 111, p. 1644–1664.
Yin, A., Kapp, P.A., Murphy, M.A., Harrison, T.M., Grove, M., Ding, L., Deng, X., and Wu, C., 1999b, Significant late Neogene east-west extension in northern Tibet: Geology, v. 27, p. 787–790.
Yin, J., Xu, J., Liu, C., and Li, H., 1988, The Tibetan plateau: Regional stratigraphic context and previous work: Philosophical Transactions of the Royal Society of London, Series A, v. 327, p. 5–52.
Yu, Z.-X., and Zheng, A.-Z., 1979, Geologic map of the Lhasa Region and geologic report: Beijing, Xizang Bureau of Geology and Mineral Resources, 284 p., scale 1:1,000,000.
Zhang, K.-J., 2000, Cretaceous palaeogeography of Tibet and adjacent areas (China): Tectonic implications: Cretaceous Research, v. 21, p. 23–33.
Zhang, K.-J., Xia, B.-D., Wang, G.-M., Li, Y.-T., and Ye, H.-F., 2004, Early Cretaceous stratigraphy, depositional environments, sandstone provenance, and tectonic setting of central Tibet, western China: Geological Society of America Bulletin, v. 116, p. 1202–1222.

Manuscript Received by the Society 22 February 2004
Revised Manuscript Received 29 August 2004
Manuscript Accepted 1 September 2004

Printed in the USA